USE OF AN AUTONOMOUS UNDERWATER VEHICLE FOR ENVIRONMENTAL EFFECTS MONITORING

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ABSTRACT

The ARCS autonomous underwater vehicle (AUV) was used on a demonstration mission with an underwater mass spectrometer to assess the effectiveness of this type of instrumentation for ocean environmental monitoring from an AUV. A tracer chemical, Dimethyl sulphide, was discharged to emulate a plume in a current field and the AUV was used to take a swath of measurements through the discharge region. Results show the spread of the tracer through the plume and the behaviour of the instrument for this purpose.

I. INTRODUCTION

Offshore oil and gas production worldwide is facing the introduction of policies leading to zero discharge or complex risk assessment to determine offshore environmental impacts. However, the present state of treatment technology is a long way from this ideal. In the interim, discharges will continue to grow with the ongoing development of the offshore oil and gas industry. This project is particularly concerned with the offshore developments on the East Coast of Newfoundland and Labrador, the most easterly province in Canada.

The Canadian East Coast, including offshore Newfoundland, has recently been considered to be a major new territory of petroleum production. All of the major oil discoveries have been in the Jeanne d'Arc Basin that covers about 14,000 square kilometers off the east coast of Newfoundland [1].

The main discharge associated with offshore oil production is called 'produced water'. Produced water is a complex mixture of inorganic and organic compounds and has the potential to be toxic to the ocean environment [2]. Typical discharge rates for produced water can be high. Over the life of the producing field, the quantity of discharge can be typically 10 times as high as the volume of hydrocarbon produced [3]. Constituents of concern include hydrolysis metals, heavy metals, petroleum hydrocarbons, nutrients, radionuclides and treating chemicals. Models of the effluent fate predict that produced water will be rapidly diluted and dispersed when discharged into the ocean, however, little real data exist [2].

The regulatory bodies for offshore oil production, such as the Canadian-Newfoundland Offshore Petroleum Board, have a mandate to ensure that offshore oil and gas activities proceed in an environmentally acceptable manner [4]. At present, monitoring typically involves sample collection techniques deployed from a ship. These methods are usually expensive and incomplete giving only a small amount of information, as they cannot account for the dynamic ocean environment. Further, with the methods of sampling, there is an increased likelihood of sample contamination and chemical degradation. Models often attempt to simulate effluent discharges, but they lack real data [3]. Required data for detailed risk analysis are also lacking [5]. New and innovative means of acquiring information are critical.

Autonomous underwater vehicles (AUVs) are self-propelled underwater vehicles that perform a pre-determined mission completely unmanned [6]. They have

moved from a state of research and development, and are beginning to receive commercial acceptance [7]. Examples of past uses are the laying of underwater cables and the operation of side-scan sonar for geo-physical and ocean bed surveys. As an AUV needs no crew, it could be miles from any support vessel or shore for hours at a time [6]. AUV technology is rapidly developing, and has the potential to be used in environmental monitoring. The main objective of this work was to design a payload for an AUV that was capable of acquiring valuable environmental data.

The main challenges associated with designing environmental payloads are centred primarily around physical constraints. Sample collection systems can cause great difficulty as large sample volumes, and duplicates are often required, and the space in an AUV is limited. Another concern associated with sampling is the sample bottle requirement. As an example, offshore sampling often requires monitoring hydrocarbons, which must be stored in glass containers. Glass is fragile, heavy and cumbersome, making it difficult for AUV use. As sampling systems have the potential to be complicated in an AUV, sensors are the preferred method for acquiring environmental data.

There are many in situ samplers available on the market for certain purposes. Two were used in this experiment: the Micro-CTD and the In-Spectr from Applied Microsystems Ltd. Examples of other types of sensors are fluorometers that can measure fluorescence in the water column and which give an indication of the concentration of phytoplankton, transmissometers that measure the turbidity or presence of particles, and current sensors to measure ocean currents.

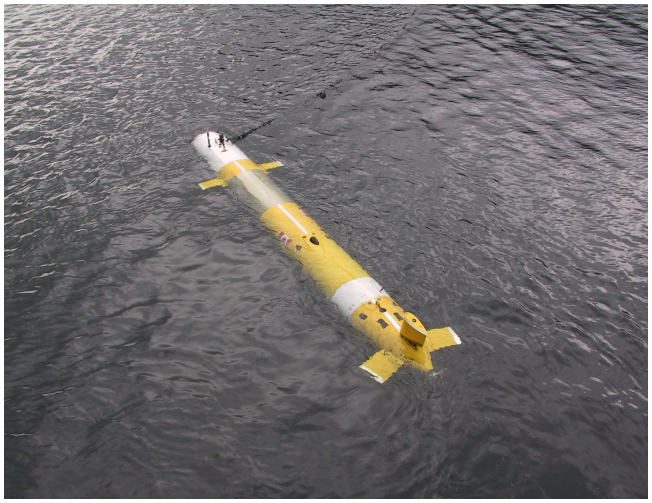

Figure 1: The ARCS Vehicle

II. THE ARCS VEHICLE

The research group for the project at Memorial University in Newfoundland worked with several other industrial and academic institutions. International Submarine Engineering Limited (ISE) in Port Coquitlam, British Columbia was one of the industrial partners. ISE Ltd. is a world leader in the design and integration of autonomous and remotely operated vehicles [8].

ISE Ltd. provided the ARCS AUV for the field sea trials component of this project. ARCS is an existing AUV developed by ISE Research Ltd. as a platform for underwater vehicle research for the Department of National Defence and the Canadian Hydrographic Service. The development and testing of ARCS took place between 1983 and 1986. Since 1987 the vehicle has been used for the development and demonstration of AUV technologies including mission controllers, navigation systems, ballast and trimming systems, and advanced power sources. Over 800 successful dives have been conducted [8]. Physically, ARCS has changed through the years to reflect is various uses. Figure 1 shows ARCS during the sea trials. Table 1 describes the specifications of the ARCS vehicle, as it existed for this project.

Length	6.4 m / 21 feet
Diameter:	68.6 cm / 27 inches
Displacement:	1360 kg / 3000 lb
Speed:	4 knots; 5.5 knots (top)
Range:	36 km / 22.5 nm with single NiCd battery; 72 km / 45 nm with double NiCd battery; 235 km / 125 nm with aluminium oxide fuel cell
Depth:	300 m / 1000 feet
Propulsion:	2.5 HP brushless DC motor
Power:	One or two 10 kWh Nickel Cadmium batteries or 100 kWh Aluminium Oxygen fuel cell
Supervisory Control:	Triple diverse full duplex acoustic telemetry link (FSK)
On-board Control:	Motorola 32-bit processor with real time proprietary control system
Navigation Sensors:	Honeywell 726 MAPS inertial navigation unit; EDO 3050 Doppler Sonar; Strain gauge depth transducer
Navigational Accuracy:	<1% of distance travelled
Obstacle Avoidance:	ISE Mesotech 200 kHz obstacle avoidance sonar

Table 1: ARCS Specifications

III. Analytical Equipment Description

Applied Microsystems Ltd. (AML), in Sidney, British Columbia, supplied all analytical equipment used in the mission. The company was incorporated in 1974 and presently designs, manufactures, and sells scientific instrumentation for water quality monitoring.

A. In-Spectr

The In-Spectr is an underwater mass spectrometer. It was developed in a partnership between AML and the University of South Florida's Center for Ocean Technology, which is an organization aimed at developing innovative marine sensors and instrumentation. They chose the mass spectrometer as the sensor of choice due to the breadth, versatility and power of the technology. Applied Microsystems Ltd secured a fifteen-year exclusive licensing agreement with the University of South Florida for the commercialization and distribution of the instrument [9].

There are three major challenges when designing miniaturized, autonomous underwater mass spectrometers. The first of these is sample introduction. This problem was overcome in the In-Spectr by using a membrane induction system [9]. This system is based on a silicone membrane introduction interface coupled to a quadrupole mass filter for detection and quantification of volatile organic compounds (VOCs) and dissolved gases to 200 atomic mass units (amu) at parts-per-billion (ppb) levels. A quadrupole mass filter uses only electric fields to separate ions through their mass to charge ratio (m/z). A quadrupole consists of four metal parallel rods or poles through which the ions being separated are passed. The poles have a fixed Direct Current (DC) and alternating Radio Frequency (RF) voltages applied to them. Depending on the produced electric field, only ions of a particular m/z ratio will be focused on the detector, all the other ions will be deflected into the rods. By varying the strengths and frequencies of electric fields, different ions will be detected thus making the mass spectrum.

The next challenge to underwater mass spectrometry, and perhaps the most difficult to overcome, is vacuum system management. Most vacuum pumps ultimately compress pumped gases and exhaust them at atmospheric pressure. This is problematic inside a closed pressure vessel system. If the pressure at the vacuum-pump exhaust port increases substantially above atmospheric pressure, the performance of the pump will degrade. This problem has been alleviated in the In-Spectr by isolating the final stage of pumping inside a separate pressure vessel. This vessel is pre-evacuated to approximately one-quarter of one atmosphere pressure prior to deployment for continuous underwater operation in excess of one week. The high vacuum required for the mass spectrometer is created in a two stage process. In the first stage, roughing pumps were used to create a vacuum with pressures near 1 to 10 Torr (133 – 1033 Pa) range. A turbo molecular pump was then used to achieve high vacuum at pressures near 10E-6 Torr (0.00133 Pa).

The In-Spectr meets the third challenge, which is to minimize power consumption. The entire system is powered by 24 VDC and consumes less than 95 Watt with all components in operation.

The underwater mass spectrometry system used for this mission is a single instrument consisting of three segregated pressure vessels. The front vessel serves as the sample collection system and contains a pump and a flow injection system. There are two modes of operation. In the discrete mode, sample water is pumped into a 1-mL sample loop, the contents of which are periodically swept into the membrane introduction mass spectrometer (MIMS) system in the central vessel by switching the flow injection valve. Pumping deionized (DI) water from a reservoir bag into the MIMS interface probe displaces samples. In this manner changes in ion intensities for selected masses can be continually compared to baseline levels in the mass spectrometer.

The second mode, and method of choice for this project, is a continuous mode of sampling. This type of sampling eliminates stream switching, and decreases lag time between sample intake and analysis. The continuous sample mode does not compare samples against a baseline level to give discrete values. Instead, it detects the presence or absence of the contaminant in the water column as the mass spectrometer is moved through the water.

The central pressure vessel contains the main components of the mass spectrometer system. These components include the vacuum chamber, mass analyser, membrane introduction probe, associated electronics, turbo molecular vacuum pump, Pentium based CPU card, 700 MB hard drive, and a power distribution board. The power distribution board was interfaced with an external computer prior to deployment, which activated the various components in sequence.

The third vessel contains two dry diaphragm pumps in series that serve as roughing pumps for the turbo pump. This chamber also acts as the reservoir for vacuum pump exhaust gas.

The practical depth of deployment for this system is presently limited to 10 metres. However, current development work is in progress to deploy the system at increased depths of 200 m. The weight of the entire system is 38.5 kg in air and is 2.5 kg in seawater. The overall

dimensions are 138 cm in length and 19 cm in diameter [10].

B. CTD Micro Sensor

The Micro-CTD is a combination of three individual sensors from Applied Microsystems Smart Sensor Series, integrated into a single housing unit. This series was designed to have standard electrical, mechanical, and communications features to allow easy integration into autonomous and remotely operated underwater vehicles. The sensors in the series include temperature, pressure, conductivity, and sound velocity sensors [10].

The Micro-CTD was designed to operate from any DC supply between 8 and 20 volts. For the deployment, the sensor was powered from a 3.6 V lithium battery. It is controlled by a software package called "Smart Talk Software", designed by Applied Microsystems [10].

An advantage to the system is that the instrument can output data in a raw data format or in engineering units. Another advantage is that the Micro-CTD can output a single scan of data or a continuous stream of data at the maximum scan rate of 25 scans per second. For this mission, the CTD scanned at a rate of one scan per second [10].

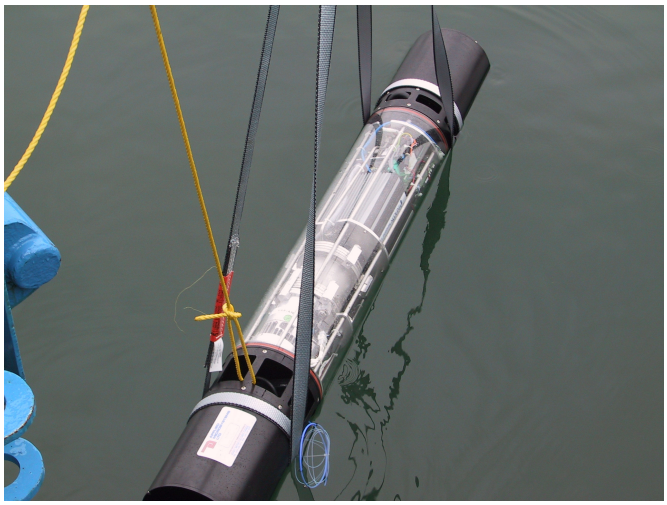

Figure 2: In-Spectr Mass Spectrometer

IV. Sea Trial Preparation

A. Mounting the Equipment

The mass spectrometer, shown in Figure 2, was brought on board the ship "Researcher" using a sling attached to a crane on the foredeck on January 31, 2002. It was determined that the weight in air was about 88 pounds and less than 5 pounds in water. This value was an approximation used to get a general idea of the buoyancy of the mass spectrometer in water. It was determined that the added mass of the In-Spectr would not affect the overall buoyancy of ARCS.

The mass spectrometer was then added to the payload bay of the ARCS vehicle. It was held in place by two identical mounting blocks used as a clamp. These blocks were designed to fit the radii of both the ARCS vehicle and the mass spectrometer. The bottom portions of the blocks were bolted to the ARCS payload bay. Figure 3 shows a picture of the mass spectrometer mounted in the payload bay of the ARCS vehicle, although the top portions of the mounting blocks were not yet added.

B. Determining an appropriate tracer

In order to demonstrate the uses of a mass spectrometer, a detectable chemical is required. An ideal contaminant to use as a plume tracer has near zero background levels and is a conservative substance. This means that it has a low decay rate and can therefore be measured in very low concentrations in the field. The preferred type of tracer for field studies according to Environment Canada is a florescent dye. The recommended dye is Rhodamine WT, which, has been proven to be a non-mutagen, to have low potential for toxicity and for adverse effects in the aquatic environment, to be readily measured in the field in the low grams per litre range of concentrations, and to have near-zero background concentrations [11].

Figure 3: In-Spectr in the ARCS payload bay

For this project, however, there was an additional consideration when choosing a tracer. It had to be compatible with the mass spectrometer. Two of the main limitations were that the chemical of choice could not be

more than 200 atomic mass units, and that it had to be relatively non-polar, that is the solubility in water needed to be relatively low, in order to pass through the membrane [10]. Rhodamine Dye WT was immediately eliminated as a tracer as it does not meet the constraints set by the mass spectrometer.

Consideration was given to using D_2O (heavy water) as a tracer since it does not degrade over time and is neutrally buoyant. However the prohibitive aspect is cost as it is much too expensive to dump many litres overboard.

There is almost no information existing about non-rhodamine tracers. Ref. [12] indicates that successful tests could be made with one version of the mass spectrometer using dimethyl sulphide. After eliminating rhodamine dye and determining that there were no other feasible options, dimethyl sulphide was selected.

Dimethyl sulphide (DMS) meets the chemical criteria for the mass spectrometer. Dimethyl sulphide is an important sulphur-containing atmospheric trace gas of marine biogenic origin. It is produced by some classes of marine phytoplankton [13]. Toxicological information provided by Material Safety Data Sheets indicates that DMS is not considered to be a hazardous substance in Canada or the United States.

It was determined that the DMS would be added at a maximum concentration of 9 litre/hour (2.5×10^{-6} m^3/s). This value was based upon a previous study performed in the area [14]. This value, then became the maximum set by the BC Ministry of Water, Land and Air Protection .

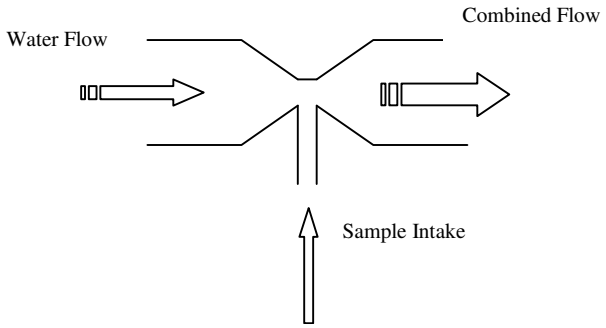

Figure 4: Flow Diagram of the Mazzei® Injector, based on MIC (2001)

The DMS was introduced to the water using a Mazzei® injector which is a venture-type injector. A pressure difference between the inlet and outlet creates a vacuum inside the injector body which initiates suction through the suction port [15]. When a pressurized fluid enters the inlet, it is constricted toward the injection chamber, which forces it to change into a high velocity jet stream. This velocity increase results in a pressure decrease, creating suction through the injector port enabling another fluid to be added to the flow. The jet stream is then diffused toward the injector outlet where its velocity is reduced again and converted into pressure energy, although at a lower pressure than at the inlet [15]. Figure 4 shows a diagram of the Mazzei® injector.

A submersible pump was used to pump seawater from Burrard Inlet through a hose and into the Mazzei® Injector. The DMS was sucked through the injection chamber, and then the combined flow was pumped through a copper pipe down into the ocean and discharged at a depth of about 10 m; see Figure 5. Copper lines were used for the DMS feed and the DMS/water lines due to the reactivity of DMS with most plastics.

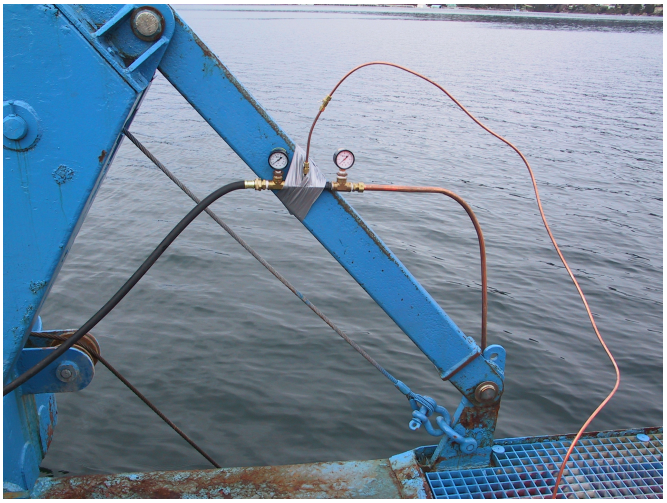

Figure 5: Tracer Dispensing System

V. RESULTS

A. Mass Spectrometer Results for DMS

A software package called "TranspectorWare" was provided with the mass spectrometer. It was used to read the mass spectrometer data in its raw form.

Figure 6 shows a screen from this software. It is a sample of the raw mass spectrometer data from February 5, 2002 plotted against "sample number". There was one mass spectrometer sample taken every 4.25 seconds.

The axes on Figure 6 represent the scan number and the electrical current. The scan number is essentially a measure of time, while the current is an indication of the presence of the chemical. Each of the five colored lines indicates a different diagnostic ion that represents the presence of different chemicals in the water system. DMS

is represented by the presence of two diagnostic ions, which are 47 and 62 (black and blue). The other diagnostic ions represent the following: toluene (91-pink, 92-green), chloroform (83-cyan, 85-brown), and benzene (78- dark green). The term "diagnostic ion" means that this mass to charge (m/z) value is a major peak in the mass spectrum of the compound of interest. In other words, if the compound is present, a peak is visible at this m/z value. On the other hand, a peak at this m/z value does not necessarily mean that the compound is present, as there may be other compounds that give you a peak at the same m/z value. For this reason, a chemical with multiple diagnostic ions should have the equivalent number of peaks present in order to confirm that it is in fact the chemical in question. For example, in Figure 6, the sharp peaks occurring only in the black line are noise, and do not indicate the presence of DMS. Since the charge on the ions using electron impact ionization is almost always +1, m/z can usually be replaced by mass. In the case of dimethyl sulphide, with chemical formula $2(CH_3)S$, the mass is 62. However, DMS also exists as methyl sulphide, with chemical formula CH_3S, which corresponds to a mass of 47, the second diagnostic ion.

The start of the peak shows the time when the chemical becomes present in the sample stream. There are several DMS peaks shown in this sample. The largest two occur at sample times 2606 and 2683. There is also a single peak present for toluene. This was at the end of the mission, and occurs at a time when the AUV was near the ship engine. It is the only toluene peak present in the data and it is believed that it was attributed to the ship's exhaust. It starts at sample number 3800. There were no other peaks for any other chemical.

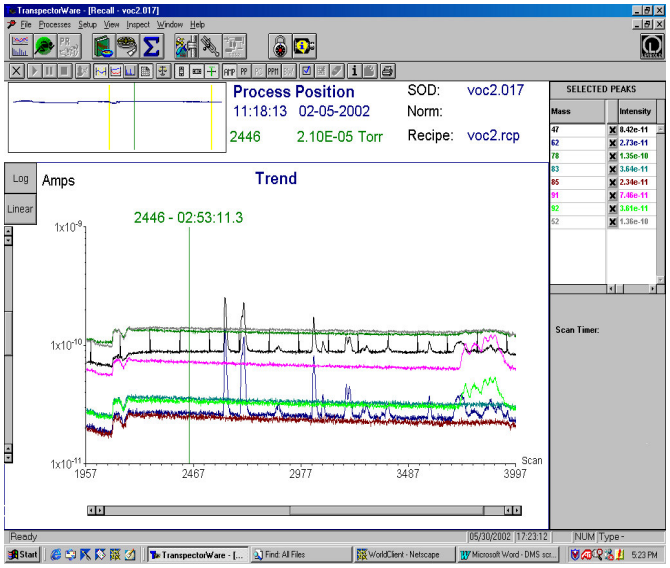

Figure 6: Mass Spectrometer Data, Raw Form

The indicator masses for DMS were isolated and plotted against the latitude and longitude of the ARCS data set using a MATLAB program. Figure 7 shows the path of the ARCS AUV during one day of trials, as well as the locations of the DMS on that day. The line shows the path, while the 'X' symbols place the presence of DMS. As shown, DMS was detected northwest of the ship when ARCS surfaced. It was later determined that the prevailing wind was carrying DMS vapours from the deck of the ship in the direction of ARCS; this indicates that the In-Spectr can sample air as well as water.

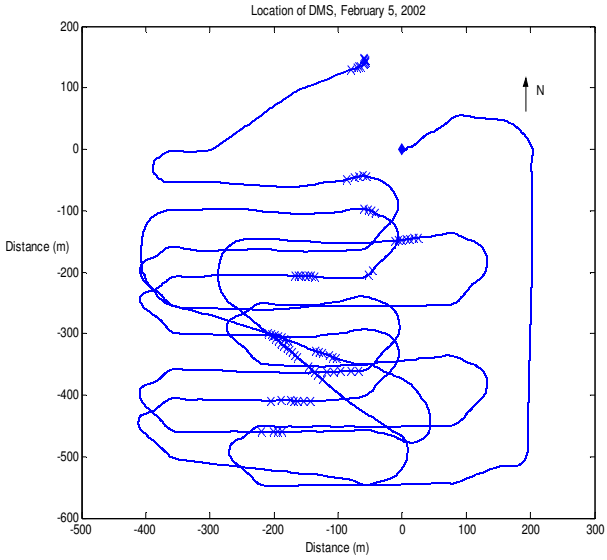

Figure 7: Location of DMS Plume, February 5, 2002

B. CTD Results

Data for conductivity (salinity), temperature and depth were collected using the Applied Microsystems Micro-CTD for all three days of field trials. Temperature was plotted against time for the three days of testing. The data for the first day are shown in Figure 8 as a sample, and are similar to the data for all days. The temperature was relatively constant with less than half a degree between the maximum and minimum temperatures. The maximum and minimum temperatures were 7.658 and 7.175 degrees Celsius respectively. The Micro-CTD can record temperature data to three decimal places.

Salinity and pressure data were plotted against time. The data for the first day is representative of all trial days and are shown in Figure 9. It can be seen that pressure increases with salinity. This trend was expected as it rained during the sea trials. The winter precipitation in

Vancouver significantly lowers the salinity at the surface [17].

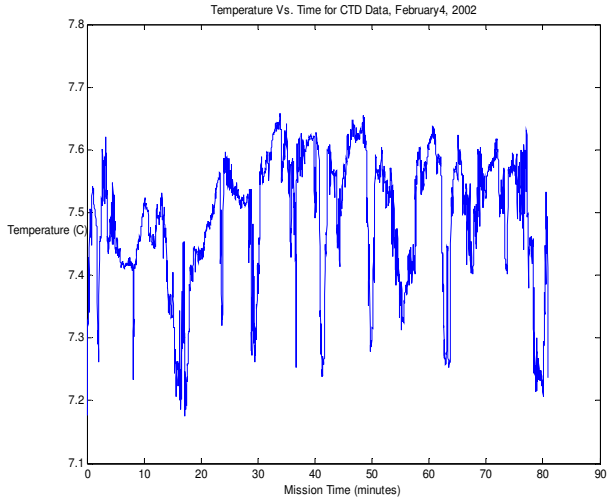

Figure 8: Temperature vs. Time

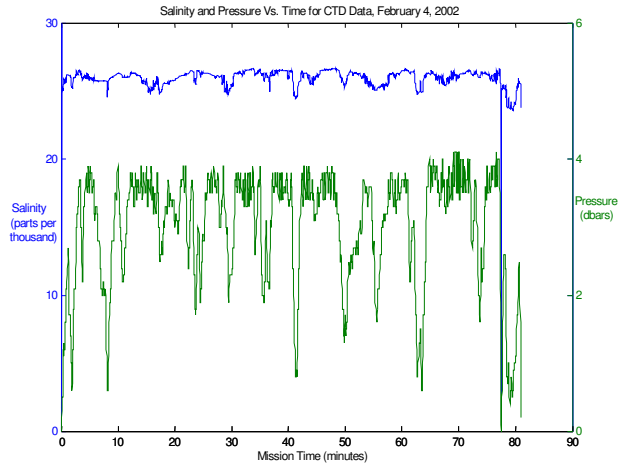

Figure 9: Salinity and Pressure vs. Time

VI. SUMMARY

As the offshore oil and gas industry continues to grow, it is important to monitor the effects of the associated discharges on the environment. To do this effectively, new and innovative means of environmental effects monitoring (EEM) need to be investigated and considered.

A project has been described that used AUV technology with innovative sensors to demonstrate the detection of environmental contaminants. It was demonstrated that the payload package used for this deployment, consisting of the Applied Microsystems mass spectrometer (In-Spectr) and Micro-CTD, can be used for plume sampling and detection.

Sample collection methods were not considered viable options for AUV use. Volume requirements are too large, resulting in too few samples. In addition, AUV launch and recovery can be time consuming during trials, and continually bringing samples back to ship or shore is inefficient. In-situ sensors can be launched for extended periods of time, resulting in a greater amount of data. Also, the potential exists for real-time measurement if the AUV is capable of sending the data back to ship or shore.

The In-Spectr was programmed to find dimethyl sulphide, a chemical that was added to the water column as a tracer. The continuous mode of sampling of the mass spectrometer was effective for determining plume location, as increases in concentration were shown. The same mode might be chosen when trying to verify an estimate of plume location. However, if this instrument was to be used for determining concentrations, the non-continuous mode should be used. For example the instrument might be considered for use in environmental regulation enforcement, to ensure that chemical concentrations are below required levels. For this type of analysis, a baseline concentration would be required. The mass spectrometer could be used to detect any chemical plume, provided the chemical in question meets the constraints of the mass spectrometer. It is possible that this instrument could provide the capability to detect certain chemicals within produced water plumes, such as hydrocarbons, although testing offshore would have to take place.

The Micro-CTD was considered appropriate for the detection of natural variations in temperature and salinity. The instrument was easy to use, and easy to install. The software packages provided with each piece of equipment are user friendly and provide directions for setting up and using the instruments. The installation was easily completed as only simple clamps were required to keep the instrumentation in place. Its small size and mass make it an appropriate instrument for AUV use.

Future work may include testing a similar package near a produced water outfall off the Canadian East Coast using the Canadian Self- Contained Off-the-shelf Underwater Testbed (C-SCOUT) AUV, an AUV project on-going and funded by NSERC.

VII. ACKNOWLEDGMENTS

Thanks are extended to Applied Microsystems Limited and International Submarine Engineering for their support in providing the field equipment used for this project.

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