

Initial Deployments of the Rover, an Autonomous Bottom-Transecting Instrument Platform for Long-Term Measurements in Deep Benthic Environments

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Abstract - Rover is a bottom-crawling, autonomous vehicle capable of making continuous time-series measurements at abyssal depths up to 6000 m for periods exceeding six months. The Rover control system and instrumentation suite are being designed at the Monterey Bay Aquarium Research Institute (MBARI), building on the earlier rover work of Smith and associates at the Scripps Institution of Oceanography. The vehicle weighs 68 kg in water and crawls on two wide tracks with a combined surface contact area of about one square meter; this provides good traction while minimizing the disturbance to benthic sediments. A typical mission scenario is to take measurements for a few days at each site before picking up the instruments and moving forward ~10 m to a new site. Up to fifty sites may be visited in a single mission.

Engineering field tests have been performed with the Rover in the Monterey Bay in California (890 m depth), and at Station M, 220 km west of the central California coast (4200 m depth). Rover operations have been observed with the ROVs *Ventana* and *Tiburon*, and with the manned submersible DSV *Alvin*. Knowledge gained from these engineering deployments has resulted in numerous modifications and improvements to The Rover.

I. INTRODUCTION

Coupling between a pelagically derived food supply and sediment community utilization of organic matter is critical to an understanding of biogeochemical cycling in the ocean [1, 2]. To resolve the coupling between pelagic and benthic systems, it is important to monitor the arrival and residence of organic matter on the sea floor using instrumentation capable of making measurements with appropriate spatial and temporal resolution. Critical questions which must be addressed to ultimately resolve pelagic-benthic coupling in the context of biogeochemical cycling are: 1) what is the quality and quantity of phytodetritus reaching the sea floor, and 2) what responses are elicited in the sediment community by the arrival of fresh detritus on the sea floor?

To address such critical questions, we began development of a new autonomous bottom-transecting instrument, the Rover, to make long time-series estimates of fresh phytodetritus arriving on the sea floor. Under NSF funding, we have been developing the Rover to concurrently monitor the fluorescence and structural features of the sediment that influence spatial and temporal heterogeneity in sediment



Figure 1. The Rover being launched from the RV *Atlantis*.

community activity, which ultimately affects the signal-to-noise ratio and resolution of measurements on biogeochemical processes in the sediments.

The Rover will be capable of conducting non-invasive time-series measurements of phytopigment fluorescence as an indicator of fresh phytodetritus on the sediment surface. Sediment community metabolism measurements (e.g. sediment community oxygen consumption) coupled with 2-dimensional oxygen imaging studies, will be conducted on the same sediments along transects including up to fifty sites without docking, recharging, or data download.

II. MISSION PROFILE

The Rover is deployed by crane over the ship's rail (Fig. 1), and freefalls to the ocean bottom. After landing and waiting for disturbed sediment to settle, the Rover measures the direction of the prevailing current and then moves upcurrent, the desired direction of travel. The vehicle moves forward ~10 meters, and waits for any disturbed sediments to settle downcurrent away from the measurement site. While the Rover is moving, a survey camera captures images of the surface sediment in the Rover's path. After movement stops, two other cameras capture visible-light close-up images of the

study site, and a scanning fluorometer, currently in development, will record the quantity and distribution of phytodetritus on the sediment. Next, two benthic respirometer chambers are inserted into the sediment one at a time. The chambers measure sediment community oxygen consumption (SCOC) for up to three days. After that time the chambers are raised and cleaned by water jets. The Rover then begins a new measurement cycle, repeating the sequence up to fifty times.

When the mission has been completed, commands are sent from a surface ship via acoustic modem, telling the Rover to release a 113 kg drop weight. The Rover then floats to the surface, where it is reattached to the ship's crane and brought back on board.

The Rover is currently in the development phase and has been deployed on eleven short test missions as of June, 2007. The longest mission has been three days, but missions with fifty measurement sites will last greater than six months.

III. VEHICLE DESIGN

A. A Unique Design Challenge

The mission requirements of the Rover are different from other ocean instrument platforms, and thus present a unique design challenge. Long deployments restrict the choice of construction materials in the corrosive ocean environment. They also require highly reliable, and possibly redundant systems to keep single-point failures from ending a mission early.

A mobile platform takes on the additional burden of a propulsion system, with its associated mechanical complexity. Mobile platforms must also have navigational sensors to provide feedback for directed motion.

High peak-power loads place demands on power sources and the electronic circuitry that controls and monitors the power. Unfortunately, systems that can control large amounts of power usually consume significant power even when the high-power load is off. While not a problem for short

TABLE 1.
Requirements for ocean instrumentation platforms.

Platform	Long Deployment?	Mobile?	High Peak Power?	Auto-nomous?
Mooring	Yes	No	No	No
ROV	No	Yes	Yes	No
AUV	No	Yes	Yes	Yes
Glider	Yes	Yes	No	Yes
Rover	Yes	Yes	Yes	Yes

deployments, this wasted power can drain a battery system on long deployments.

Finally, autonomous platforms must, by definition, be capable of carrying out their missions without a human "in the loop." Beyond completing the mission as intended, they must also have the intelligence and additional circuitry to detect and respond to system failures, at best continuing to collect science data and at least avoiding loss of the vehicle. Autonomy also implies isolation from external power sources, and so the platform must perform these tasks with a finite energy supply provided by batteries.

These various requirements, and how they apply to different ocean instrument platforms, are shown in Table 1. Note that only the Rover requires all of these capabilities. This is not to say that any one of these functional requirements is particularly onerous, as they are features of many other platforms. It is instead the combination of required features (e.g. high peak loads combined with long deployments) that makes the design challenging. As a result, some parts of the Rover can't be purchased commercially or copied from existing designs, but must be designed for this application.

B. Instrumentation

The design of the Rover platform is driven by the instruments it is required to carry. These instruments include:

- Benthic respirometers (2)
- Respirometer chamber cameras (2)
- Fluorometric scanners (2)
- Survey camera
- Current meter
- Guest instruments (up to 3)

Control and recovery of the Rover is aided by the following:

- Acoustic modem
- Argos satellite beacon
- VHF radio beacon
- Xenon flasher beacon

The most important measurement the Rover makes is of sediment community oxygen consumption. SCOC measurements are made by two respirometer chambers, each 30 cm in diameter and 20 cm deep (Fig. 2). Oxygen in each



Figure 2. The respirometer chambers on the front of the Rover.

chamber is measured by an optode (model 3830, Aanderaa Data Instruments, Bergen, Norway), with a third optode external to the chambers providing reference measurements of ambient water.

Each chamber has three valves on top that are opened during chamber insertion to avoid compressing the sediment to be studied, and during extraction to avoid suction effects. The valves must remain tightly closed during respirometer incubations to exclude exchange with external water. Valves are hydraulically actuated with water pressure provided by a pump (model 5T, Sea-Bird Electronics, Bellevue, Washington) on each chamber, feeding the three valves in series. The hydraulic valves consume much less power than a solenoid-actuated valve, and their slow operation minimizes any pressure disturbances.

A pair of crossed rods, which are rotated at 6 rpm by a small motor during respirometer incubations, stir the water inside each chamber. Stirring is required to avoid stratification of oxygen-depleted water near the sediment surface.

After each respirometer measurement, the chamber is extracted from the sediment, and a cleaning pump sprays water across the interior surfaces of the chamber to remove adhering sediment that could affect subsequent measurements.

Two chamber cameras (model Nova, Insite Pacific Inc., Solana Beach, California) capture close-up images of the sediment inside the respirometer chambers. These cameras have integral white LEDs to provide illumination. Images are captured before chamber insertion to record any macrofauna present on the sediment, and after chamber insertion to verify proper insertion depth and chamber sealing.

Two fluorometric scanners quantify the abundance, size, and distribution of phytodetritus on the sediment surface prior to respirometer measurements. Each scanner will scan a 30 cm by 35 cm patch of sediment directly beneath each respirometer chamber by moving a fluorometer (model ECO, WET Labs, Philomath, Oregon) back and forth across the study area in 1 mm steps, thus forming a fluorometric map of any phytodetritus present.

A survey camera will capture images of the area in front of Rover every few meters during movement between measurement sites. These images will provide a continuous record of the area traversed by the Rover, and will aid in surveys of phytodetritus, megafauna, and structural features. Two strobe lights (custom design, Scripps Institution of Oceanography, La Jolla, California) will provide illumination for the survey camera.

An acoustic current meter (model 2D-ACM, Falmouth Scientific, Inc., Cataumet, Massachusetts) measures water currents for navigation and as a record of ambient conditions during deployment. The current meter also contains a compass and a tiltmeter so that the Rover's heading, pitch, and roll can be determined.

The Rover can accommodate up to three guest instruments. The guest instrument ports supply switched power and an isolated RS-232 serial data connection. The power

consumption and duty cycle of any guest instruments must be low enough to not adversely affect the energy remaining for other vehicle needs.

The Rover's acoustic modem (model ATM-887, Benthos, North Falmouth, Massachusetts) is a data telemetry modem that has been modified by Benthos to provide a burn-wire output. The burn-wire is used to release the Rover's recovery drop weight, and the data telemetry channel is used to send commands and receive status during a mission.

To aid in locating the Rover once it returns to the surface after a mission, it carries a VHF radio beacon (model RF700A1, Novatech, Dartmouth, Nova Scotia), a xenon flasher (model ST-400A, Novatech), and an Argos satellite beacon (model AS900A, Novatech)

C. Mechanical Design

The mechanical configuration of the Rover is driven by two requirements: it must transit across very soft, sticky mud, and it must be capable of changing its buoyancy by 113 kg during each mission. In order to traverse the deep ocean mud, rover uses two 46 cm-wide, lugged tracks that present a 0.94 m² footprint to support the Rover's in-water weight of 68 kg. This low surface-contact pressure (72 kg/m²) allows the Rover to float over the mud to minimize disturbance and suspended sediment.

Two brushless propulsion motors (model EC 60, Maxon Precision Motors, Fall River, Massachusetts) are mounted at the rear of the chassis. Each motor drives a 308:1 reduction gearhead and is contained in an oil-filled housing. The motors are rated at 400 watts each, but they consume less than 100 watts in this application. The gearhead output shafts are connected to the rear wheels via drive belts.

The rover is 2.6 m long, 1.7 m wide, 1.5 m tall, and weighs 1136 kg in air. The vehicle frame is constructed of several 2.5 cm-thick black UHMW plates with grade 2 titanium pipes and brackets (Fig. 3). Most of the 0.54 m³ of 625 g/L syntactic foam is in the form of 13 blocks, each having a volume of 28 L and rated for 6000 m depth. Six more "football" floats on



Figure 3. The Rover frame.

the upper titanium tubes provide additional flotation and can be adjusted fore and aft to trim the Rover's pitch.

At the front of the Rover are two respirometer racks, which are lead-screw-driven vertical carriages that insert and extract the respirometer chambers. The two racks are completely independent to provide redundancy in case one system fails.

The 113 kg steel drop weight is suspended below the Rover's center of gravity using a series of lever-arms that are retained by a redundant pair of standard Benthos burn-wires. The Rover is ballasted to weigh 68 kg in water with the drop weight present, and to be 45 kg buoyant when the drop weight is released. Batteries and electronic components are stored in 43 cm-diameter cast titanium spheres, which provide some additional flotation.

The 3 cm-diameter lift line for the Rover is attached to a titanium tube at the top of the vehicle between the two main bulkheads. To aid in recovery, the lift line is attached to a spar buoy with a 10 m-long polypropylene line. The spar buoy is a 6.5 m-long fiberglass pole with a large football float in the middle and a steel weight at the bottom. The spar buoy holds a large flag, the VHF radio beacon, and the xenon flasher almost 3 m above the water, greatly enhancing the visibility of the Rover during recovery operations (Fig. 4).

D. Electrical Design

The main vehicle computer (MVC) is housed in a cast titanium sphere rated to a depth of 6000 m. The MVC is a PC/104 format stack consisting of four cards: an ARM 9 computer card (model TS-7200, Technologic Systems, Fountain Hills, Arizona), a real-time clock daughter card (model TS-5620, Technologic Systems), a 12-port isolated serial card (model Xtreme/104 Isolated, Connect Tech, Inc, Guelph, Ontario), and a 5-port Ethernet switch (model PRV-1059, Parvus Corp., Salt Lake City, Utah). The TS-7200 was chosen mainly for its high performance-to-power-

consumption ratio. The 200 MHz Cirrus ARM9 processor, 32 MB SDRAM, compact flash interface, and 10/100 Ethernet interface deliver more than adequate computational performance while consuming only 2 Watts during operation, and less than 0.5 Watts while idling.

A network video server (model 241Q, Axis Communications, Lund, Sweden) is used to capture images from the two chamber cameras. A higher resolution survey camera will store images on its own memory.

Also housed in the same sphere are electronics for power conversion and switching. Two off-the-shelf serially controlled 8-channel relay boards (model CK1610, Carl's Electronics, Oakland, California) are used to switch power from the battery bus to all of the peripheral loads. This was a quick and inexpensive solution that enabled deployment and testing of the Rover; however, the cost of this short-term solution is wasted power, and no current, voltage, or ground-fault detection. Custom load controller boards are currently being designed that will have low quiescent power (a few mW), but are capable of providing up to hundreds of watts of galvanically isolated power at various voltages, and provide current and voltage monitoring, overcurrent protection, and ground fault detection. Until the load controllers are installed, the Rover has two DC-DC converters providing +5V and +12V (models UHE-5/5000-Q12 and UHE-12/2500-D24, Datel, Mansfield, Massachusetts) to loads that can't operate directly from the +30 V bus.

All of the motors on the Rover, with the exception of the stirrer motors in the benthic respirometers, are brushless DC motors housed in oil. Attached to each oil-filled motor housing is a small 1-atm titanium pressure housing in which a motor driver/controller board (model EZSV23, All Motion, San Jose, California) is mounted. The motor controllers communicate with the MVC through an RS-485 multi-drop bus. The stirrer motors are brushed DC motors housed in Fluorinert.

Rover power for short deployments is provided by alkaline battery packs that are housed in a single separate titanium sphere. These alkaline packs consist of 240 D cells, with multiple diode-isolated strings of 20 cells providing a nominal 2.9 kW-h at +30 V. Eventually for long-term deployments, two spheres of lithium primary batteries will provide up to 19 kW-h of energy.

E. Software Design

The MVC runs a Linux 2.4-based system from the manufacturer, modified by MBARI to support the isolated serial card and to use BusyBox as the command shell. The modular approach for adding UNIX commands to BusyBox results in a command shell that is tailored for use in the Rover and, therefore, much smaller than a standard Linux shell environment.

Vehicle and instrument control applications are implemented in the Ruby programming language. Ruby is an object-oriented scripting language and interpreter implemented in C, allowing it to be readily ported to



Figure 4. The Rover and spar buoy during recovery operations.

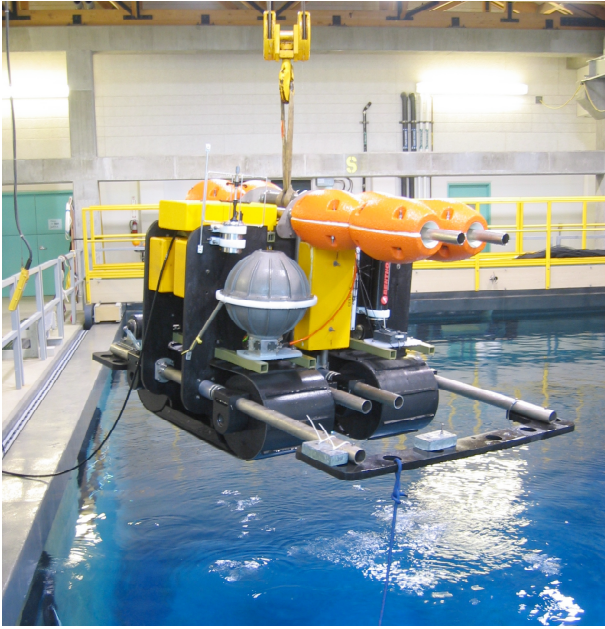


Figure 5. The Rover over MBARI's 1.4 million liter test tank.

embedded computing platforms without the need for a supporting tool-chain. Ruby lends itself well to creating concise, robust, and readable application code owing to its clean syntax, strong object-oriented support, and high-level programming features. These attributes allow the engineers on the Rover team to isolate failure logic and apply the methods across the code-base in a consistent manner, improving overall fault detection and recovery.

The Rover has a rather simple operational scenario consisting of four phases: launch, movement, measurement, and recovery. The design of the Rover control application directly reflects those phases with classes created to manage each phase and a main class that controls the transitions between the phases. The phase class objects are designed to run as separate execution threads whose progress can be monitored by the main control class. Faults that occur during the execution of a phase can be detected or trapped by the main thread, allowing the opportunity for recovery procedures to correct problems and attempt another phase execution.

IV. SHALLOW DEPLOYMENTS

A. Overview

Initial testing of the Rover's ballast and trim was performed in MBARI's 1.4 million liter saltwater test tank (Fig. 5). The tank's large size of 9 m width by 14 m length and 10 m depth provided enough volume to test the Rover's drop weight release mechanism and the vehicle's ability to move on the bottom.

The first at-sea testing took place from the R/V *Pt. Lobos* in Monterey Bay at a site about 40 km offshore and at a depth of 890 m. The Rover was launched by crane and allowed to freefall to the bottom, where it was observed by ROV

Ventana. The purpose of the first dives was to test launch and recovery mechanisms and procedures, and to verify basic Rover movement on the seafloor.

B. Propulsion System

Although the Rover was able to maneuver on the first dives, there were numerous issues with the track drive mechanism. Sometimes while driving forward, the tracks were seen to stop briefly while the drive wheels continued to spin; this did not occur when driving in reverse. The problem is that a track system with rear-wheel drive is in tension on the bottom half of the tracks and is loose on the top half while driving forward. This was causing the 1.5 cm-high treads on the tracks to interfere with parts of the chassis, such as protruding bolts and bulkheads. The problem was corrected by increasing the overall track tension slightly, and by installing smooth plastic sheets on the bottom of the chassis directly above the tracks. Wheel slippage was eliminated by knurling the surface of the drive wheels to increase contact friction with the tracks.

The tracks were observed to sit just on the sediment surface without sinking in, as was intended. However, sediment clinging to the track surface is carried forward on the top half of the tracks, acting as a conveyor belt, and dumped at the front of the vehicle near the respirometers. Stiff brushes added to rear of the vehicle where the track leaves the seafloor have been effective in removing this sediment at the source.

Even with the brushes in place, simply moving too rapidly can kick up unacceptable quantities of sediment. Initial Rover speeds of 7 cm/sec were found to be too disruptive, and have since been reduced to less than 2 cm/sec.

The compensation oil reservoir levels for the main propulsion motors were greatly diminished after the first Rover dive. This is an important issue, as any loss of oil large enough to be observed during a short deployment could add up to a large and disabling loss during a long deployment. On the second dive, oil was observed escaping from the propulsion motor shaft seals. Rebuilding the motor output shafts and replacing the o-ring seals with lip seals has completely eliminated the oil loss problem.

C. Acoustic Modem

The acoustic modem is a vital component of the Rover's recovery system, as it is the means by which the drop weight can be commanded to release. Although all of the Rover dives thus far have had an ROV or DSV present to manually release the weight if necessary, future Rover missions may be recovered from ships without other assets on the seafloor. In this case, an inability to communicate with the Rover would preclude its recovery.

Acoustic modem performance was highly variable on the first Rover missions. Although the modem should function at ranges over 6 km, operation was spotty at less than 1 km, and the manual weight release had to be used to recover the vehicle on multiple dives.

There were at least two causes for these problems. First, although the topside modem transducer was deployed from the

surface ship at a depth at least ten meters below the hull, the transducer was still susceptible to acoustic interference from both the ship and surface waves. Second, although the transducer is susceptible to interference from the back, it is a directional device that must be pointed at the Rover to achieve an acceptable signal-to-noise ratio. However, on days when strong winds or surface currents were present, the ship's drifting would cause the modem transducer to trail behind and point away from the vertical direction.

The interference issue was addressed by adding a syntactic foam baffle (model for AT-421 transducer, Flotation Technologies, Biddeford, Maine) to the topside transducer. The baffle provides a high acoustic impedance to sound coming from the rear of the transducer. Unfortunately, it also causes the transducer to float, so 26 kg of lead weight was added to keep the transducer down. This added weight also solved the problem of the transducer trailing behind the ship. Now reliable communications are routinely established at ranges exceeding 4 km.

The price for this enhanced performance is additional effort to deploy and recover the heavy topside transducer package. What once could be handled by one person is now a two- or three-person operation.

D. Accelerometers

Recording accelerometers were mounted on the Rover for its first two dives to monitor vehicle motion [3]. The Rover's dynamics are difficult to model, and so little was known about how it would fall through the water column, and how great an impact it would make with the seafloor. Acceleration in all three translational axes (heave, surge, and sway) was measured at a rate of 62 Hz for the entire dives. Because the accelerometers also sense the gravity vector, vehicle pitch and roll could also be determined.

The results, shown in Table 2, reveal the Rover to be quite stable during descent. Trim remains remarkably level given the asymmetric distribution of weight and drag forces, and any oscillations are small and very slow. The landing impact of 1.33 G includes the static force of gravity, so the additional loading of one-third G is entirely within acceptable limits. Fig. 6 shows the landing impact in detail. After a single

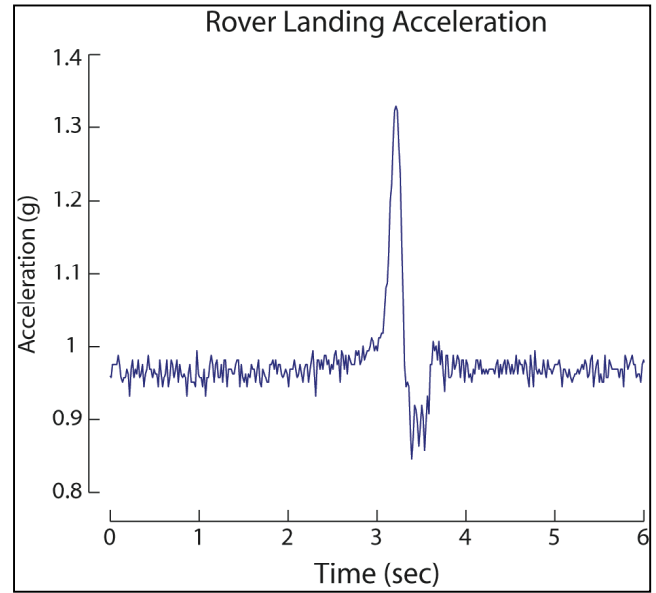


Figure 6. The Rover landing recorded by an accelerometer.

bounce, the Rover has settled in about 1 sec after impact. As expected, the highest G loads were seen during recovery while the Rover was being lifted by the ship's crane during somewhat rough weather. These recovery loads are still within design limits and resulted in no damage to the Rover.

V. DEEP DEPLOYMENTS

A. Overview

After solving numerous minor issues with the shallow dives in Monterey Bay, the Rover was deployed to a depth of 4 km at Station M, 220 km west of the central California coast. Rover operations on the bottom were observed directly from the DSV *Alvin* (Fig. 7), and remotely with the ROV *Tiburon* on subsequent cruises.

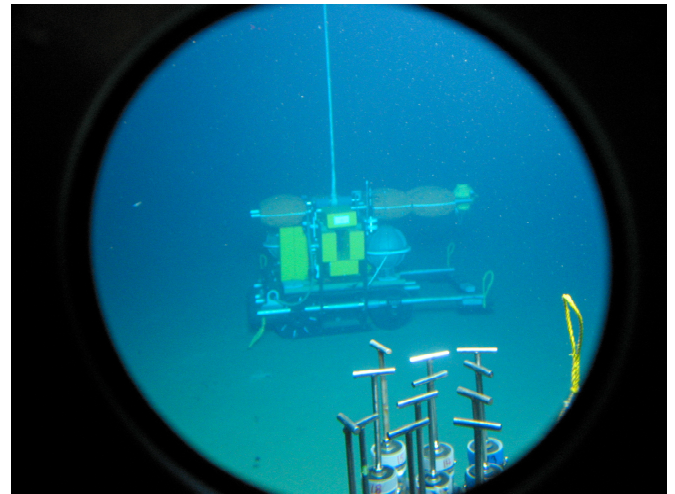


Figure 7. The Rover as seen through DSV *Alvin*'s viewport.

TABLE 2

Vehicle dynamics recorded on the Rover's first dives.

Descent rate	36 meters/minute
Pitch during descent	5 degrees up
Roll during descent	6 degrees to port
Pitch variation about mean	3 degrees
Roll variation about mean	1.5 degrees
Period of pitch and roll variation	35 seconds
Peak load on landing	1.33 G heave down
Peak load during recovery	>3 G surge aft

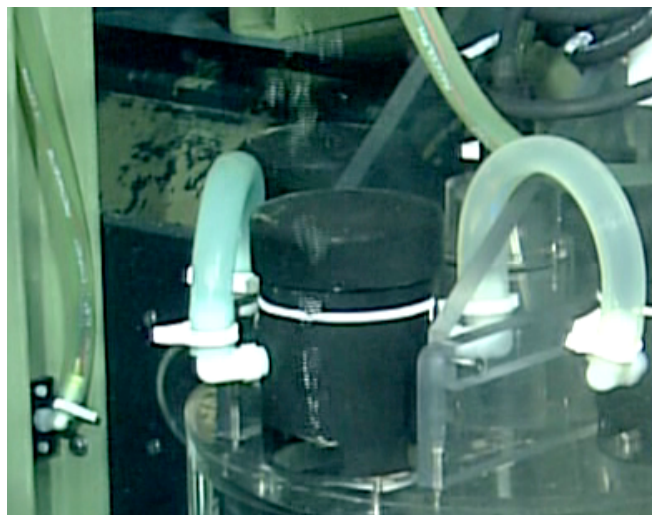


Figure 8. Air bubbles escaping at 3950 meters depth.

Because basic Rover operation was made reliable in the earlier shallow dives, the deep dives presented the opportunity to refine the operation of the benthic respirometers, and to record the first measurements of sediment community oxygen consumption.

B. Benthic Respirometer Measurements

Only minor problems were encountered during testing of the respirometers. On one dive, the switch that senses when the chamber is inserted to the correct depth into the sediment got stuck and did not active. As a result, the chamber kept going until the rack limit switch was activated, and no damage was done. Had the rack limit switch failed, the motor controller overcurrent sensor would have tripped, protecting the motor and the rack. This was a good demonstration of the Rover's layered structure, where systems are expected to eventually fail and other systems, hopefully seldom-used, activate to prevent disaster.

During a subsequent dive, air bubbles were seen to be escaping from one of the respirometer valves just as it was opened (Fig. 8). This was somewhat surprising to all observers present, who are not accustomed to seeing air bubbles at a depth of 3950 m. However, if the entire 14 L volume of the chamber were full of air at the surface, and that air remained trapped during descent, then that same air would have a volume of about 35 cm³ on the bottom at a pressure of approximately 400 atm. While this simple calculation doesn't account for effects of temperature and the dissolution of the gas into the water, it is a plausible explanation for the estimated 5–10 cm³ of air seen escaping from the valve. Other MBARI researchers have observed similar events on previous ROV dives [4].

The valves are supposed to open near the beginning of the dive to bleed the air from the chambers and prevent high-

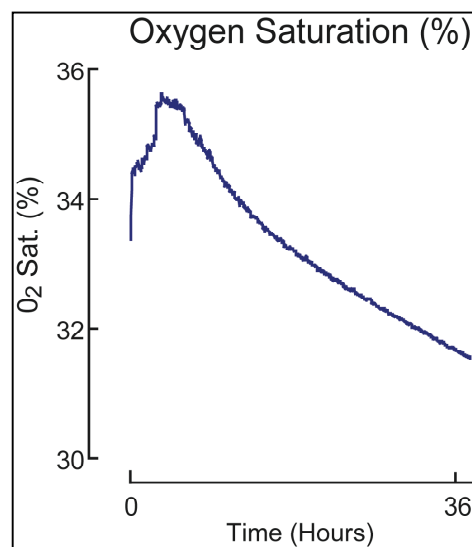


Figure 9. Respirometer oxygen levels over 36 hours.

pressure air from forcing oxygen into any part of the respirometer. Upon reviewing the Rover's computer logs, however, it was established that delays in launching the vehicle had caused the valves to be actuated while still on deck. Timing was adjusted on subsequent dives to ensure that the valves were not opened until the Rover was in the water.

Data from the first 36-hour incubation are shown in Fig. 9. Oxygen saturation levels begin high, and then slowly decay as oxygen is consumed by fauna in the sediment.

VI. CONCLUSIONS AND FUTURE WORK

Initial deployments of the Rover have been very successful. Thanks to the excellent vantage points provided by the ROVs *Ventana* and *Tiburón*, and DSV *Alvin*, numerous minor problems have been identified and addressed. No dive has been perfect yet, but then one doesn't learn as much from a perfect dive.

In the coming year the fluorometric scanners and the survey camera will be built and tested. The Rover will also be connected to the Monterey Accelerated Research System (MARS) cable for further testing in Monterey Bay (<http://www.mbari.org/mars>). The MARS cable will provide a continuous power and data connection to the Rover, which will greatly facilitate the development of the Rover's autonomous software.

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