Feasibility Analysis of an 11,000 m Vehicle with a Fiber Optic Microcable Link to the Surface

S. E. Webster, Woods Hole Oceanographic Institution
Woods Hole Oceanographic Institution
266 Woods Hole Rd.
Woods Hole, MA 02543, USA
swebster@whoi.edu

A. D. Bowen, Woods Hole Oceanographic Institution
Woods Hole Oceanographic Institution
266 Woods Hole Rd.
Woods Hole, MA 02543, USA
abowen@whoi.edu

***Abstract*-This paper discusses the feasibility of an 11,000 m underwater system that utilizes a battery-powered vehicle connected to the surface by a single channel fiber optic microcable. The proposed system has several benefits over conventional remotely operated vehicle (ROV) solutions for ultra deep applications. It avoids the prohibitively expensive tether and winch otherwise necessary for 11,000 m work. Due to its relatively small size and low weight, the system allows for fast mobilizations and use on a variety of platforms. This concept also allows the vehicle to travel tens of kilometers away from the surface ship, which would be beneficial in applications where the surface ship has limited maneuverability such as under-ice work in the Arctic. This analysis focuses on the feasibility of using a microcable tether with a 450 N (100 lb) breaking strength housed in a constant force payout canister. Tension in the cable is modeled for current conditions in three areas of interest to the scientific community—a deep Western Pacific trench, the Arctic and the Juan de Fuca Ridge—and found to be well within the microcable's working limit.**

INTRODUCTION

Our goal is to create a practical 11,000 m system using an appropriately designed self-powered vehicle connected to the surface vessel by a small, lightweight reinforced glass fiber of up to 40 km in length. The vehicle will be able to operate untethered as a fully autonomous vehicle, and also as a self-powered vehicle employing a 0.8 mm diameter optical fiber tether for real-time telemetry of data and video to its human operators on a surface ship. We term this new class of vehicle a Hybrid Remotely Operated Vehicle (HROV).

A. Proposed Vehicle

The proposed HROV, depicted in Fig. 1, will have capabilities of both an AUV and ROV. While operating untethered, the vehicle will enjoy the freedom of movement of an AUV, which has proven highly effective for a variety of survey operations [1,2,3]. While connected to the surface with a lightweight fiber optic tether, high bandwidth two-way communications will permit the return of high quality video and sensor data, enabling close-up inspection, sampling, and instrument deployment/recovery operations to be conducted under the command of pilots and scientists onboard a research vessel. Our vehicle concept allows conversion from an AUV to a Hybrid-ROV (HROV) while at sea, thereby enhancing the science mission capabilities on a single cruise.

At present, only one deep submergence system is capable of reaching the deepest parts of the worlds oceans; the Kaiko ROV, built and operated by JAMSTEC [4]. This vehicle is extremely large and as a result has high annual operating costs. The size of the handling traction winch and A-frame require a that the system use the 105 m (345 ft.) dedicated support vessel *Yokoska*.

B. Scientific Need

The scientific imperatives for development of an 11,000 m HROV are numerous. In addition to supporting deep diving that cannot be accommodated any other way at present, the application of our HROV concept also has significant implications for providing new capabilities to the US oceanographic fleet. The HROV system we propose is intended to be deployed on a wide range of ships with the only requirement being the ability to host a fiber-optic CTD cable (of University-National Oceanographic Laboratory Systems (UNOLS) standard 8.2 mm (0.322") diameter to maintain compatibility with existing UNOLS standard CTD cable winches and sheaves) on a standard CTD winch, without the need for dynamic positioning of the vessel. We highlight below several of the key scientific missions that would greatly benefit from such a development. These are consistent with many scientific objectives stated in various reports from national panels and meetings conducted over the past decade [5,6,7,8].

Broadly stated the scientific objectives of an 11,000 m vehicle fall into the following five categories:

1. Investigation of seismic, geo-hydrological and macro/microbiological problems in accretionary prisms on the inward slopes of oceanic trenches in subduction zones worldwide, primarily at the margins of the Pacific Ocean basin.
2. Investigation of ultra-slow spreading seafloor geology, biology and geochemistry (rock and fluids) [9]. Many ultra-slow mid-ocean ridges (MORs) occur in geographic regions where weather windows are extremely narrow or there is ice cover (e.g. the Southern Ocean between 40°-50°S, Australian-Antarctic Discordance, and in the Arctic—the Gakkel Ridge [10]).
3. Investigation of magmatic, hydrothermal and volcanic activity in the deepest portions of oceanic transforms in extensional tectonic settings—i.e. pull-apart basins, propagating rifts, and microplates.
4. Event response—tied to mid-ocean ridge [11] and subduction zone magmatism and tectonics and to human events (e.g. accidents) where planes, ships or other debris must be located and surveyed at the deepest ocean depths quickly and efficiently.
5. Under-ice operations, such as the ultra slow spreading MOR recently discovered in the Arctic [10], where the

vehicle must be able to operate independent of the vessel motion and with large horizontal offsets.

This paper focuses on determining the feasibility of the proposed lightweight fiber optic tether for the foreseeable applications of the HROV.

HROV CONCEPT OVERVIEW

A. Fiber Optic Microcable

The proposed microcable tether is a single-mode dispersion shifted fiber made by Corning Corporation that is only 0.8 mm in diameter (see Fig. 1.) It has been used for many years in various US defense related applications where it is known as fiber optic microcable (FOMC). FOMC development for underwater vehicle applications dates back to the early 1980s by the United States Navy [12]. Twenty kilometers of FOMC can be wound into a self-supporting spool the size of a cookie tin (~30 cm diameter x 15 cm tall). One kilometer of FOMC weighs slightly less than 0.5 kg in water, and it has a breaking strength of approximately 450 N (100 pounds). The spools can be wound into nearly any length and the tension required to pull FOMC from the spool can be accurately controlled during the winding process.

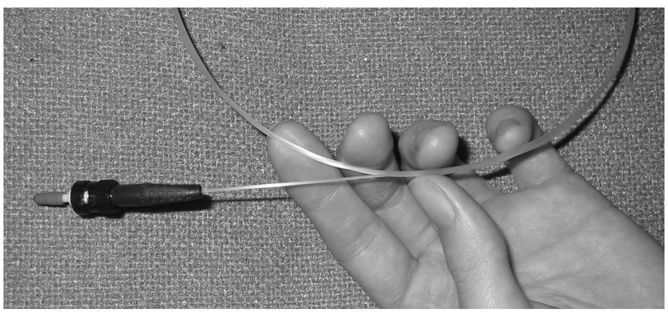

Fig. 1. Fiber optic microcable.

B. Deployment

The HROV requires an innovative deployment technique. Fig. 1 graphically illustrates the HROV deployment concept. We will employ three payout canisters: one on the depressor, one on the vehicle, and one on the descent anchor assembly. As tensions rise due to movement of any of the three elements or currents, FOMC passively pays out from the canisters, preventing the microcables from exceeding their breaking strength.

1. **Deployment**: The first panel in Fig. 1 shows the HROV deployed from the support vessel using 0.322” diameter fiber optic CTD cable. Primarily, this cable serves as a method to both physically launch the HROV and enable transition to the FOMC in a controlled environment away from surface effects. The armored cable depressor would be deployed deep enough to keep the depressor clear of the vessel and to penetrate any surface currents. We estimate the operating depth for the depressor will be approximately 1000 m, however, this could be adjusted depending on vehicle operating depth, current profile, etc.
2. **Descent**: Once the vehicle has reached the desired depressor depth, the vehicle is released from the armored cable depressor and begins a free fall to the seafloor using a descent anchor assembly. FOMC canisters on both the depressor and anchor assemblies allow FOMC to payout during the descent as required. Both canisters will pay out passively as the tensions demand, the canister on the descent anchor will pay out primarily due to vehicle motion and the canister on the depressor will pay out as the depressor moves due to vessel/surface motion.
3. **On Bottom**: Once the vehicle has reached the bottom, the descent anchor assembly will be released from the vehicle. The HROV is then free to maneuver. The vehicle conducts its mission as required. During this phase, FOMC will pay out from the vehicle canister (up to 10 km) as the HROV traverses the bottom, and from the depressor canister due to any vessel motion. Horizontal currents could also draw more FOMC from the descent anchor assembly if needed.
4. **Ascent**: Once the HROV has completed its work, the vehicle jettisons the FOMC canister and drops its ascent weight for the trip to the surface. As with descent, the vehicle guides itself to a rendezvous with the armored cable depressor whereupon the HROV latches to the armored cable depressor and is winched to the surface for recovery.
5. **FMOC Recovery**: With the HROV aboard, the FOMC system can then be recovered. While the armored cable depressor is being brought aboard, the descent anchor assembly is called (acoustically) to drop its ascent weight to begin transit to the surface. As this is underway, a small FOMC recovery winch on deck retrieves the FOMC for repacking and reuse. The descent anchor assembly is then recovered.

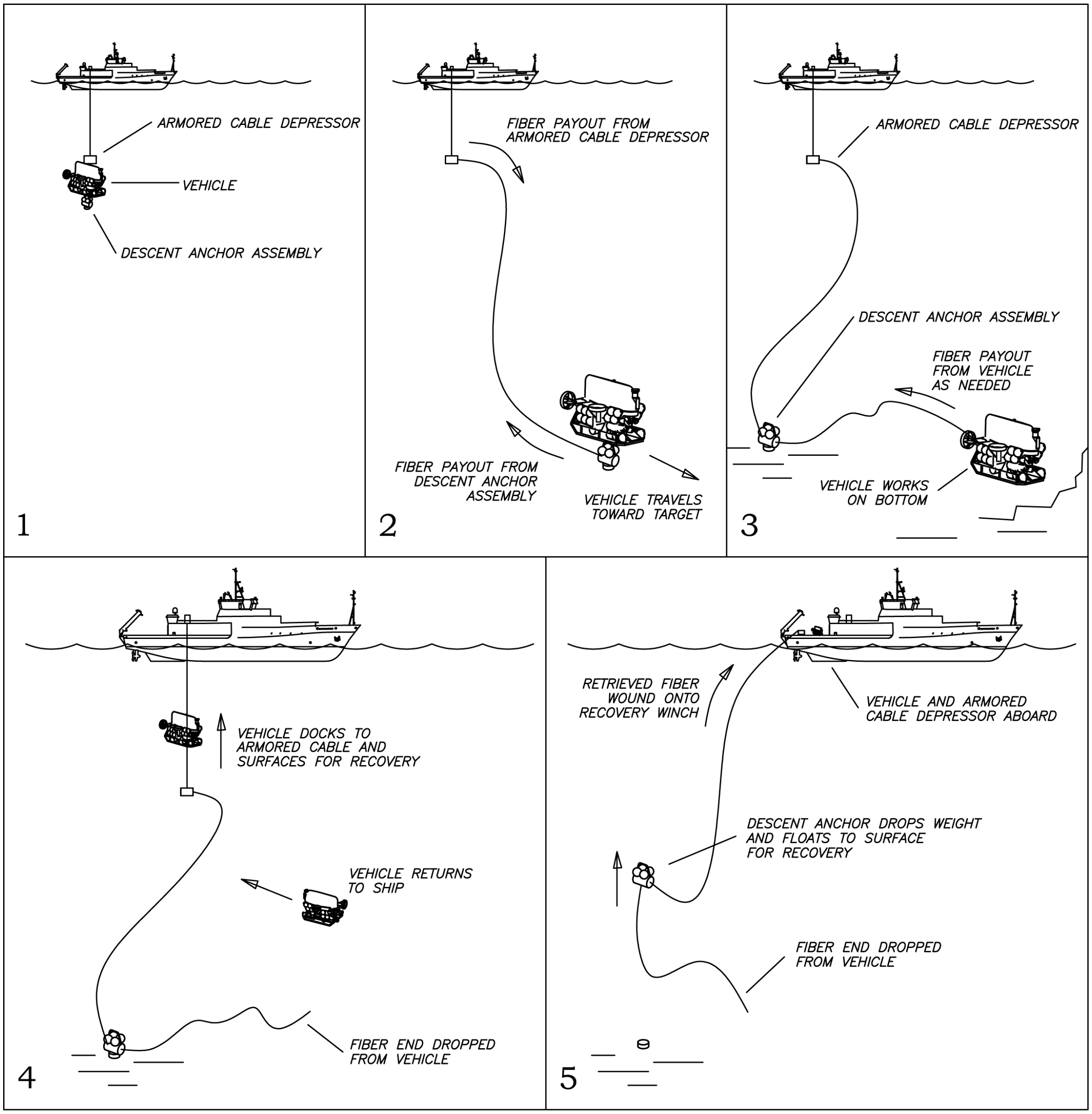

Fig. 1. The Hybrid ROV Design Concept: The HROV will be capable of operating to 11,000 m depth as an ROV with a fiber optic microcable tether, and operating without a tether as an AUV. Panels 1-5 depict deployment, operation, and recovery.

TETHER FEASIBILITY ANALYSIS

The success of the proposed HROV deployment system hinges on predicting and controlling the loads experienced by the FOMC. To evaluate the feasibility of this approach, we have conducted an extensive set of numerical simulations to estimate the axial and longitudinal loading of the FOMC in the expected current conditions, and to show how the FOMC tension varies with the length of fiber in the water column. The static cable analyses were performed using 'WHOI Cable,' a general-purpose code for calculating the static and dynamic response of moored and towed oceanographic systems [13]. The model is fully three-dimensional and includes the effects of torsion, bending, and geometric and material nonlinearities. We assumed that one end of the FOMC was fixed to the launch depressor at the surface; the other end was fixed to the HROV descent anchor assembly. The descent anchor assembly was either 11,000 m or 6,000 m deep and within 100 m horizontally underneath the ship. The 100 m horizontal offset was chosen as a representative "watch circle" for a non-dynamically positioned vessel trying to keep station. We performed the analysis for other horizontal offsets up to several kilometers and found that tensions did not rise appreciably.

A. Operational Envelope

Fig. 2 shows a sample of the output from the WHOI Cable program for a 17,000 m long FOMC with the HROV underneath the ship. The plot on the left shows the physical layout of the FOMC in the water column. The upper right plot shows the tension of the FOMC along its length. The bottom right plot shows the specified current profile as a function of depth.

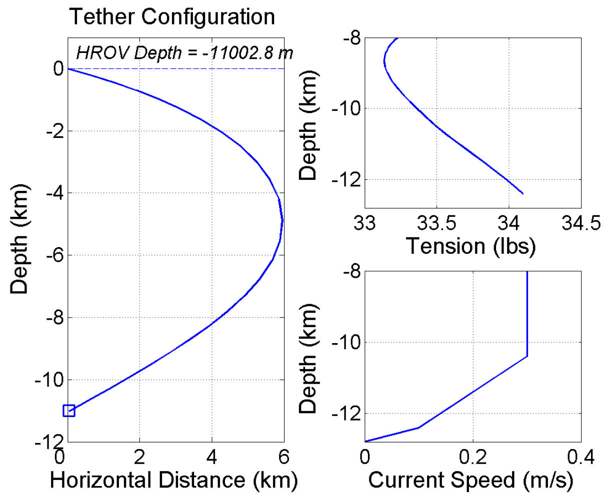

Fig. 2. Example static analysis result.

The simulation was first run using four different idealized current profiles with the vehicle at 6,000 m and 11,000 m. Fig. 3 shows the current profiles used. The lowest current profile, 0.2 m/s, is constant, the other three current profiles each taper starting at 6,000 m deep to 0.1 m/s at 1000 m and to 0.0 m/s at 12,000 m. (The current profile plotted in Fig. 2 shows this as well.) These idealized current profiles were used to establish the viable operating regime of the HROV.

For each current profile we modeled the tension in the FOMC as its length increased in 1,000 m increments. To protect the FOMC the maximum payout force used is half of the microcable's breaking strength, roughly 225 N (50 lbs.) This payout force is plotted along with the FOMC tension to show where the cable tension balances the payout force.

In Fig. 4 we see that when deployed to 6,000 m the HROV can operate in the 0.45 m/s tapered current profile with roughly 9,000 m of FOMC in the water column.

In comparison, Fig. 5 shows that the HROV deployed to 11,000 m can operate in the 0.3 m/s tapered current profile, but not above. In 0.3 m/s maximum current the FOMC will pay out to around 13,500 m, while above that the system exceeds our design limit of 20,000 m of FOMC.

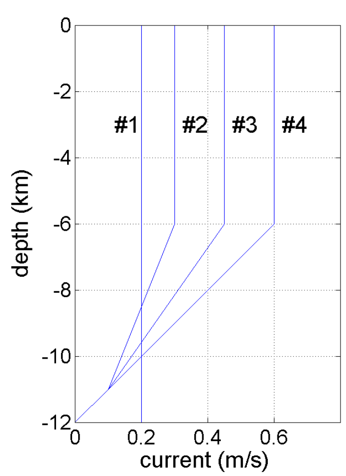

Fig. 3. Current profiles used in simulations.

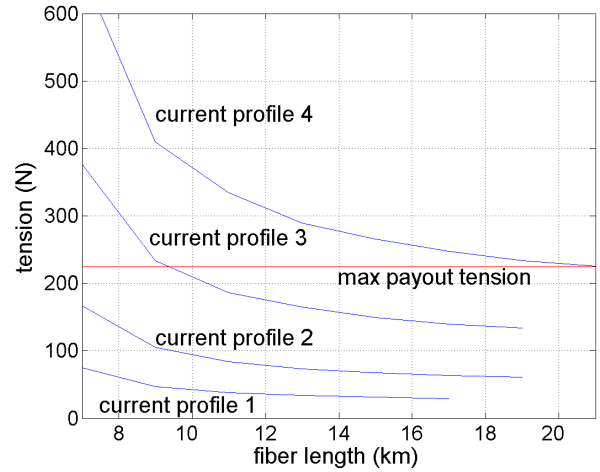

Fig 4. FOMC tension versus length for 6,000 m deployment.

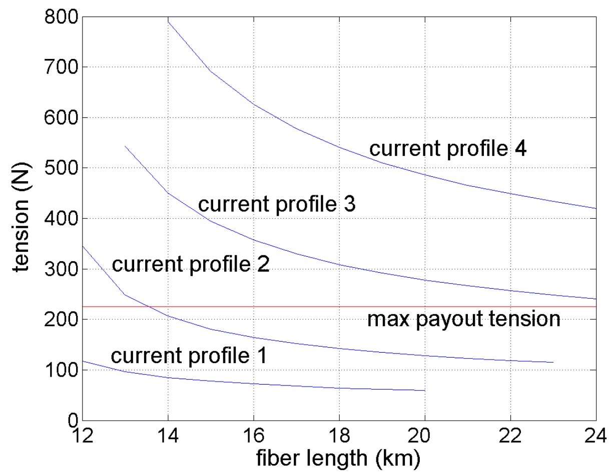

Fig. 5. FOMC tension versus length for 11,000 m deployment.

As noted above, our deployment strategy involves using a clump weight to start the FOMC below the highest surface current. These results show that this system can operate in conditions where the maximum current below the depth of the clump weight does not exceed 0.3 m/s in 11,000 m or 0.45 m/s in 6,000 m.

B. Site Specific Operation

We have also expanded the analysis to use measured current profiles from three potential operating areas: Arctic [14,15], Juan de Fuca [16], and the Izu-Ogasawara Trench [17]. The Arctic currents in 4,000 m of water have a maximum of 0.32 m/s at the surface that drop off quickly after 300 m to 0.04 m/s at the bottom. The maximum Juan de Fuca currents in 3,500 m of water are more extreme, starting at 0.41 m/s on the surface and dropping to 0.17 m/s at 500 m (based on the mean currents plus a 0.10 m/s offset for tidal variations.) These data indicate that the current profiles for the Arctic and Juan de Fuca are all will within the operating envelope found above.

Fig. 6 shows the FOMC tension versus length for the Arctic and Juan de Fuca. Again we assumed that the FOMC was attached to the launch depressor at the surface, and the HROV descent anchor assembly on the bottom.

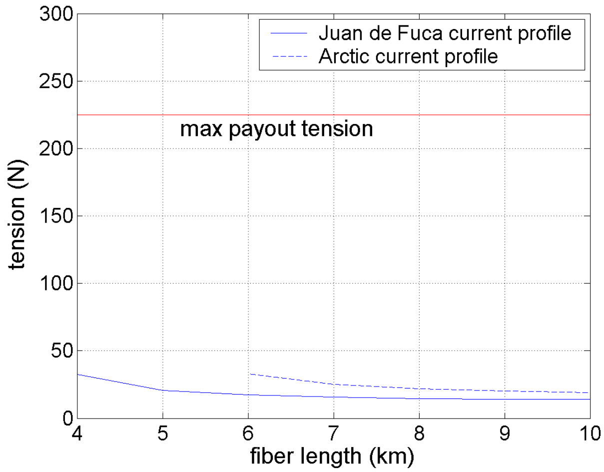

Fig. 6. FOMC tension versus length for the Arctic and Juan de Fuca.

In both cases, the results show that the vehicle could reach the bottom with FOMC tension not exceeding 33 N (7.4 lbs) using cable lengths only slightly longer than the water depth (well within the 20,000 m limit). This is not surprising, as the measure profiles are less demanding than the acceptable idealized profile.

The Izu-Ogasawara Trench is representative of deep Western Pacific trenches that are the deepest part of the ocean floor. The Izu-Ogasawara Trench runs north-south for roughly 500 nautical miles off the southeastern side of Japan. The current data available for the Izu-Ogasawara Trench show that below 4000 m (the deepest data are from 9100 m) the current never exceeds 0.04 m/s. No current data are available above 4000 m. Compared to the idealized current profiles used in the 11,000 m simulations above, it is clear that the current for the depths available will not significantly affect the tension in the FOMC. The tension will, instead, be dominated by the current profile above 4000 m, which is unknown.

ANALYSIS CONCLUSIONS

Tension in the FOMC decreases monotonically with the length of FOMC in the water column to a minimum tension that is determined by the current profile. The system will work in currents up 0.45 m/s in 6,000 m, and up to 0.3 m/s in 11,000 m.

Conclusions from the simulations using actual current data are very positive. The FOMC tensions are much lower than the first set of simulations predicted (because the current profiles are much less severe) and are roughly an order of magnitude less than our desired maximum pull out force. This indicates that the FOMC, with a 450 N (100 lb) breaking strength and 225 N (50 lb) working load, is more than adequate for operating under these conditions. The use of the depressor weight was shown to be unnecessary other than keeping the FOMC clear of the ships propellers.

FURTHER WORK

A proposal was submitted to ONR, NSF and NOAA to build a full ocean depth hybrid system based partly on the analysis presented in this paper.

We plan on performing dynamic analyses of the system to examine the effect of inertial loading from the heave of the ship on the fiber tension, also using WHOI Cable. Inertial loading may cause FOMC to be spooled out from the payout canister on the clump weight. Simulations will be used to verify that the loads on the FOMC do not exceed working limits.

If funded we plan to carry out full scale deployment trials of a prototype system with the proposed FOMC tether.

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REFERENCES

[1] M.A. Tivey, H.P. Johnson, A. Bradley, and D. Yoerger. "Thickness of a submarine lava flow determined from near-bottom magnetic field mapping by autonomous underwater vehicle," *Geophysical Research Letters*, 25(6):805-808, March 1998.

[2] M-H. Cormier, W.B.F. Ryan, A.M. Bradley, D.R. Yoerger, W. Jin, A. Shah, J. Sinton, R. Batiza, K. Rubin, "Variable extrusive emplacement mechanisms in the axial region of the east pacific rise," unpublished.

[3] D.R. Yoerger, A. Bradley, B. Walden, H. Singh, and R. Bachmayer, "Surveying a subsea lava flow using the Autonomous Benthic Explorer (ABE)," *International Journal of Systems Science*, 29(10):1031-1044, 1998.

[4] S. Umino, P.W. Lipman, and S. Obata, "Formation of subaqueous flow lobes, observed on KAIKO ROV dives off Hawaii," *Geology*, 28:502-506, 2000.

[5] H.P. Johnson, "Probing for life in the ocean crust with the LEXEN Program," *EOS, Tran. AGU,* 84(12), March 2003.

[6] *The Future of Marine Geology and Geophysics*, NSF Workshop Report, NSF Div of Ocean Sciences, December 1996. Online at: *http://www.joi-odp.org/FUMAGES/PDFs/FUMAGES.pdf*

[7] *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration*, NOAA Report, October 2000. *http://oceanpanel.nos.noaa.gov/panelreport/ocean_panel_report.html*

[8] *Link 2002 Symposium, Sea and Space Experts Join to Develop Undersea Technologies*, NOAA-NASA Symposium, 2002. Available online at: *http://www.thelinkproject.org/Outcomes-Products/MTSsummarypaper.pdf*

[9] H. Dick et al., "A long in situ section of the lower ocean crust: results of ODP leg 176 drilling at the Southwest Indian Ridge," *Earth and Planetary Science Letters*, 179:31-51, 2000.

[10] M.H. Edwards, G.J. Kurras, M. Tolstoy, D.R. Bohnenstiehl, B.J. Coakley, and J.R. Cochran, "Evidence of recent volcanic activity on the ultraslow-spreading Gakkel Ridge," *Nature* 409, 808-812, 2001.

[11] RIDGE 2000 Science Plan. Available at: http://ridge2000.bio.psu.edu/R2k_sci_plan_2003.pdf

[12] J.H. Dombrowski, W. Kerr, and S.J. Cowen., "Development and fabrication of the fiber optic microcable," Technical Report NRAD TR-1620, 1 October 1993. Available online at:

http://www.spawar.navy.mil/sti/publications/pubs/tr/1646/tr1646.pdf
[13] J.I. Gobat and M.A. Grosenbaugh, "WHOI Cable v2.0: Time Domain Numerical Simulation of Moored and Towed Oceanographic Systems," Technical Report WHOI-2000-08, Woods Hole Oceanographic Institution, 2000.
[14] R.A. Woodgate, K. Aagaard, R.D. Muench, J. Gunn, G. Bjork, B. Rudels, A.T. Roach, U. Schauer, "The Arctic ocean boundary current along the Eurasian Sloe and the adjacent Lomosov Ridge: water mass properties, transports and transformations from moored instruments," *Deep-Sea Researc*h, I, 48:1757-1792, 2001.
[15] K. Aagaard, "On the deep circulation in the Arctic Ocean," *Deep-Sea Researc*h, 28A(3):251-268, 1981.
[16] G.A. Cannon, D.J. Pashonski, "Variation in mean current affecting hydrothermal plumes and the Juan de Fuca Ridge," *J. Geophys. Res*., 120(C11):24965-24976, 1997.
[17] S. Fiji, D. Yanagimoto, K. Taira, "Deep current structure above the Izu-Ogasawara Trench," *J. Geophys. Res*., 105(C3):6377-6386, 2000.