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Woods Hole Oceanographic Institution

Elevators—Autonomous Transporters for Deep Sea Benthic Sample Recovery

by

M.F. Bowen
P.J. Bernard
D.E. Gleason
L.L. Whitcomb

January 2000

Technical Report

Funding was provided by Woods Hole Oceanographic Institution.

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M.F. Bowen, P.J. Bernard, D.E. Gleason (WHOI), L.L. Whitcomb (JHU)

Version 1.0
4 January 2000

*Figure [1] Evening recovery of a sample transporter
called an elevator*

Figure [2] Artifact elevator deployment

Figure [3] Science elevator secured on deck

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Abstract

Two classes of sample recovery devices have been fabricated for use with the *Jason* deep diving remotely operated vehicle (ROV). One class includes custom-built, autonomous vertical transporters (AVTs) that are capable of raising numerous benthic samples and other payloads to the ocean's surface independent of the sampling ROV. AVTs are more commonly referred to as sample "elevators". Elevators are inexpensive to construct and can be deployed and recovered many times during the course of a single ROV dive in order to reduce wear and tear on the more expensive ROV. A second class includes a range of custom-built end effectors and articulated scoops that ROV operators mount onto the vehicle's manipulator and sampling cradle according to required sampling tasks. This report describes the design, fabrication, operation and navigational tracking of these various non-destructive sampling devices. A ballast and flotation spreadsheet is provided, which allows operators to customize each elevator deployment and sample recovery scenario while the ROV continues work on the benthos. (162)
Keywords: ROV, sampling, autonomous.

Figures [7] and [8] Roman era lamp, recovered by Jason's mitts

Figure [9] The ROV Jason transporting a recovered amphora

Figure [10] Jason prepares to place an amphora into an elevator bin

1.0 Introduction

Engineers, researchers and operations specialists of the National Deep Submergence Laboratory (DSL) of the Woods Hole Oceanographic Institution (WHOI) have been operating remotely operated underwater vehicles (ROVs) since 1983 (Bowen, Fornari et al. 1993). Engineers of the WHOI Deep Submersible Operations Group (DSOG) conceived the first autonomous vertical transporter (AVT), or sample "elevator", in 1980. In 1989, the first DSL elevator was built to complement work being done by the deep diving ROV *Jason* at an ancient shipwreck site in the Tyrrhennian Sea off Sicily (Figures [5], [9] and [10]) (McCann, Freed 1994). There have been numerous elevator designs applied on twelve *Jason* cruises since then depending on lessons learned in the field and the sampling goals of scientists and researchers working with DSL (Gegg 1999; Gleason 1999).

Elevators are designed to descend to the ocean floor and return to the surface without a cable attached (autonomously) and at calculated rates (Figures [11] and [44]). Before it is released from the surface ship, an elevator is armed with a steel weight (Figure [24]). The mass of the weight sinks the system to the bottom. An expert navigator estimates where on the surface the elevator should be released so that it lands on the bottom nearby the site to be sampled. The elevator cannot actively change its horizontal direction during ascent or descent, it is directed only by the navigator's knowledge of prevailing currents in the water column. When sampling is complete, an acoustic signal is sent subsea by the navigator that triggers a burn-wire release, the weight is dropped, and the elevator returns to the surface (Figure [31a]). There the elevator is recovered by the research vessel if no other vehicles are deployed, or by small boat if the vessel is maintaining station or running tracklines.

More versatile ROVs, which can actively move along any combination of three axes, may or may not be deployed when a "single axis" elevator is deployed, however if an ROV already is submerged, there is an added operational risk of the two becoming entangled (Figure [11]) (Last, Williams 1991; MTS 1984; Waddington 1998).

Each elevator is custom-built, usually in the field, and is capable of raising numerous delicate benthic samples and other payloads to the ocean's surface independent of the sampling ROV. Elevators are inexpensive to construct and can be cycled through many vertical trips during the course of a single ROV dive. This method of sample recovery reduces both the need for a large ROV payload capacity and accumulated ascent/descent fatigue on the more valuable ROV. It is now understood that the most successful elevators are simple, flexible, quasi-expendable and almost under-engineered. There have been at least three generations of elevators used over the years and there is a certain acquired art to proper construction. Every elevator is an experiment in engineering. There are some guidelines presented here, however elevator design has never been "frozen".

During all DSL cruises, elevators are treated as non-destructive sample transporters. When built and deployed properly with an ROV system, they can present to shipboard experts intact samples in such prime condition that the ROV-to-elevator-to-ship transition sustains its purpose as an invisible, reliable component of normally difficult remotely controlled sampling processes (Figure [6]) (Bowen 1990, Bowen 1995). If an elevator is too rigid or has inappropriate construction features, expensive and hard-won samples can forever be damaged or lost.

Elevators occupy just one of two classes of sample recovery devices that have been fabricated in the field for use with *Jason*. A second class includes a range of custom-built manipulator end effectors and articulated scoops that ROV operators mount onto the vehicle according to the required sampling tasks (Figures [7], [8] and [45]). All of these devices are rated to depths of 20,000 feet (6,000 meters) (DSP&L 1991).

This report describes the design, fabrication, operation, dynamics and navigational tracking of various AVTs and modular sampling tools. The report itself (in .pdf format), report images (in .bmp, .jpg or .gif formats), and a ballast and flotation spreadsheet (in .xls format) are provided on a CDROM in an included sleeve. Spreadsheet capabilities are explained in the text. It will allow future elevator operators to customize their own elevator deployments and sample recovery scenarios while their ROV continues work on the seafloor.

2.0 General Elevator Construction

2.1 System Flexibility

One given in elevator design is that every cruise mission will be different, perhaps every deployment will be different, so adaptations are frequent and must be invented on the spot. A key word in elevator design is "flexibility". The frame and basket are designed to adapt quickly to new sampling demands. Scientists will arrive on board and provide new or unusual gear that they wish

to deploy. DSL engineers and technicians work closely with scientists in all phases of equipment development. The basic elevator designs shown in the accompanying figures are effective.

Figures [12] and [13] Freestanding on deck, detail of upper framework

2.2 Framework and Flotation

DSL elevators are designed to be inexpensive, modular, and easy to assemble or disassemble for storage and shipping. The main framework takes advantage of a readily available standard U.S. pipe sizes and matching fittings (Ryerson 1995). It is primarily constructed of 1- $\frac{1}{2}$ " IPS schedule 40 pipe made from 6061-T6-aluminum alloy combined with Hollander Speed Rail[®] pipefittings. The fittings are similar to those mass produced to construct temporary stadium handrails and scaffoldings (Figures [13] and [14]). Each fitting contains stainless steel setscrews that allow the framework to be modified using a single Allen[®] wrench. The pipe is procured in ten-or twenty-foot long sections that can be cut to length using a portable bandsaw. These aluminum and stainless materials are one-person portable and can withstand prolonged immersion in salt water, which makes them ideal for use at any depth offshore.

Figures [14] and [15] Upper framework, assembled onto four uprights

Elevator frameworks are freestanding when fully assembled and secured on a level deck, however they act top heavy when the decks are rolling, so more tie-downs and caution are advised. Some elevators are placed and secured onto large sawhorses, so that modifications can be made up off deck level (Figures [12] and [15]).

The design of the frame is based upon the need for mounting ballast for deployment and descent, mounting flotation to raise the elevator back to the surface, and for securing payloads introduced on the ocean floor in the form of samples. The top and bottom sections of an elevator are permanently welded subassemblies. Four upright pipes are added to complete the basic frame. This modular approach allows for rapid assembly or disassembly, and requires only minimal storage space on deck, an advantage to operators who modify payload capabilities from dive to dive.

2.2.1 Upper Framework

The upper framework section supports a number of flotation spheres (Benthos® 17-inch diameter glass floats enclosed in yellow plastic hard hats) and a Benthos long baseline (LBL) transponder (Figures [12], [13], [14] and [15]). The top is smaller than the bottom to reduce drag and prevent toppling. The dimensions of the upper frame reflect the number of flotation spheres that are required for each deployment. The spheres and the acoustic transponder are attached to the frame with stainless steel hose clamps. The transponder communicates with a ship transducer and an LBL navigation network to allow tracking by navigators. The transponder also has the ability to burn a wire and release the elevator's ballast weights.

Figure [16] Lower framework with bin lids open

2.2.2 Lower Framework

The lower framework section is made wide for some stability and increased drag (Figures [6] and [16]). It normally consists of the sample basket and bins, sampling devices, device triggers, manual pull pins, a burn-wire weight dropper and an expendable steel descent weight. It is essentially a mirror image of the upper frame but with sample baskets, shelves and bins added to it. The lower frame's dimensions can be modified based on the requirement for varying weight-dropping specifications and the mass of samples to be recovered. It accepts four upright poles

and supports the descent weight and weight dropper on vertical axis, directly beneath the center of buoyancy. Additional hose clamps and custom mounting hardware are screwed onto the lower frame to secure sampling devices, other instrumentation and offload packages as required.

2.2.3 In-Water Stability

Recovered samples plus metal framework plus instruments plus the descent weight all comprise a single sinking mass that opposes the lifting effects of the flotation spheres. What appears to be a disproportionate vertical separation distance between the main mass on the lower framework and the flotation on the upper framework ensures a powerful stabilizing moment, keeping the elevator upright at all times so no samples are lost overboard (Figure 31d). This arrangement also protects the retrieved samples because they stay six to eight feet below surface disturbances during recovery operations. Flexing in the upright pipes also improves shock absorption, which can be caused by towing and recovery tasks.

2.3 Sample Basket Types

Various baskets and bins can be secured to the lower elevator frame. A well thought-out elevator basket greatly expands the ROV's sampling capacity, reduces ROV cycles to the surface, reduces the labor involved with deployment of individual sensors or instruments, and maximizes bottom time in the long-term. Science elevators usually have smaller basketry than archaeological elevators because science samples and measurement devices generally have higher densities than do artifacts (Figures [2] and [3]).

2.3.1 Science Baskets

Science elevators carry a sturdy basket with walls made of virtually indestructible Fiberglas[®] grating that can withstand rough treatment from geologic samples, coring devices, heavy water samplers and metal instrument housings (Figures [19] and [20]). The grating does not absorb significant amounts of water and has a relatively low specific gravity. Fiberglass baskets may have a number of sequentially labeled, deep or shallow sample compartments, which are held together with Tyraps[®] and stainless hose clamps.

Figures [19] and [20] Science basket and instrumentation

Science baskets may have one or more docking stations on board made up of two docking pins (Figures [19] and [29]). *Jason* can dock to the elevator on the ocean floor by inserting two alignment cones into the pins and maintaining some amount of forward thrust. While *Jason* is docked, the ROV operator can shift attention from flying to manipulation tasks. The manipulator can pick up or drop off instruments, samples may be offloaded and release pins can be triggered as required.

During dives when the Imetrix Exact® navigation system is required, an elevator can be modified with two additional customized bays to help deploy a network of transceiver units (Figure [21]). Once delivered to the bottom, pairs of transceivers are lifted out by *Jason* and moved to

Figure [21] and [22] Exact transceiver in delivery bin and deployed

precise network locations surrounding the sampling site (Figure [22]). At the end of sampling operations, perhaps days later, the transceivers are reloaded onto another elevator and recovered.

DSL is now considering the use of extruded plastic baskets, which were originally manufactured for the automotive parts industry. These baskets have properties similar to fiberglass baskets but add a ballast and flotation advantage in that they are nearly neutrally buoyant. Although extruded baskets cannot be disassembled like fiberglass baskets, they are ideal for shipping elevator parts and they can be moved or stacked by forklifts.

2.3.2 Artifact Baskets

In contrast to science baskets, artifact baskets are woven onto padded frameworks (Figure [23]). The basket material is pliable synthetic netting, similar to trawl netting, which has performed well for the recovery of delicate, irreplaceable archaeological samples. Artifact baskets have hinged lids that can be closed by the ROV to cover samples and protect them during ascent and recovery. Every effort is made to assure the cruise archaeologists that the artifact basket design delivers samples without evidence of transport. Anytime the transport is considered unacceptable, modifications are undertaken before the next deployment.

Figure [23] Pliable artifact basket with hinged lid

2.4 Ballast and Weight Dropper

A deployed elevator travels passively to the bottom and usually lands within one to two hundred feet from the sample site. When sampling tasks by the ROV are complete, the elevator and its payload are released on demand by a combination of an acoustic transponder, a burn-wire, and a mechanical advantage release (Figure [25]) attached to stack of carbon steel plates (Figure [24]). When the Benthos transponder on top of the elevator's framework receives a coded release burst from the surface ship, it sends an electrical current through two insulated wires to the burn-wire, a loop which is exposed to seawater in the lower framework. The successful start of a burn is relayed by another acoustic signal back to the surface. The wire dissolves in about six minutes, releasing the tip of a lever arm and a small shackle attached to the weight stack. The elevator, now buoyant, rises away from the stack, which will not be recovered. (*Jason* has filmed this process.) Steel plates are used for ballast because they have a relatively minimal affect on the deepsea environment and can be easily added to elevators according to the ballast weight required per deployment (Figure [44]).

Figures [24] and [25] Steel weight stack and weight dropper detail

The elevator is tracked as it ascends via the same transponder. An elevator makes only one trip to the bottom and back before it must be reset. During each reset a new burn wire and ballast stack are installed and transponder functions are tested. This simple weight dropping method provides for quick turnaround on deck; an operation that can usually be accomplished in the time required to unload recovered samples.

Some of the most fascinating areas of research for scientists (and ROV pilots) are the rugged vent fields along volcanic ridge crests. These mountainous underwater regions are truly dynamic, containing deep crevices that change from year to year often opening new chasms that can swallow an entire elevator and eliminate the possibility of its effective use by an ROV.

The "canyon-landing" scenario has been played out on at least two cruises. DSL has applied a weight dropper variation to help an elevator survive landings in rough terrain. Fifteen to twenty feet of light wire rope separated the elevator from its drop weight. The elevator floated safely in the water column above the expendable drop weight and dangerous bottom features. On another occasion even the extended wire was too short and an elevator landed inside a narrow crevice. It appeared that the top of the elevator was just even with the plane of the bottom leaving the lower frame further down inside the crevice. *Jason* entered the crevice in order to reach the equipment, a rather undesirable operating condition. However the elevator was positioned with one side braced against a wall and because it was suspended above the weight on a long line the ROV pilot was able to rotate the elevator to whatever side he needed to address.

DSL builds elevators with both acoustic and manual (ROV) releases. The drop weight cable is always rigged with a pull pin in case the acoustic release fails. Releasing an elevator manually by ROV and pull pin is a hazardous solution but may be worth the risk if the elevator carries valuable equipment or samples.

Steel plates may be added to an elevator for a second purpose, that of temporary ballast. If required, they can be secured by bungee cords and pull pins, which the ROV can later remove on the bottom. This practice increases the possibility of improving elevator trim (increasing buoyancy) and portability from one sampling site to another.

2.5 Bungee Cord, Rubber Bands and Stainless Pull Pins

A proven method of ensuring that sample equipment or instruments are not lost during deployment is to tie them into or onto the elevator. One should never assume that an instrument is heavy enough to remain inside an elevator bin when it is lowered into waves. Everything riding on an elevator must be under some restraint, either temporary or permanent. Permanent restraint is often accomplished with duct tape, Tyraps®, hose clamps, bolts and line.

The two most effective and inexpensive materials used for temporary restraint are No. 64 rubber bands and 1/2-inch diameter bungee cord. Rubber bands hold objects with small surface

areas and air weights up to about thirty pounds, such as tube cores and their quivers, small hand tools used by the ROV manipulator, major and minor water samplers and site markers.

DSL has learned that there is a tendency for operators to bridle larger, heavier objects with too many rubber bands. This malpractice can lead to frustrating manipulation tasks on the bottom. Rubber bands in the deep ocean are surprisingly strong and stretchy. Most rubber bands on the surface break after stretching a foot, but can stretch two to three feet before breaking at depth. For example, *Jason* has now used *Alvin*-style double major water samplers. Two well-placed rubber bands are more than sufficient to hold them onto an elevator. The double majors have about a thirty pound air weight and a negative twenty pound water weight.

For temporarily restraining heavy, large instruments the most effective method uses bungee cord combined with stainless steel pull pins. The largest object to date that DSL has deployed by bungee restraint was a ocean bottom magnetometer, which weighed fifty pounds in air and negative twenty-four pounds in seawater. The magnetometer was tied to the elevator in a manner similar to securing a portable object to a ship's deck. A length of bungee cord was tied as two parts with one end of each tied to the frame and the other ends looped with soft eyes. The two pieces were stretched with one eye passing through the other and a large pull pin (a large stainless steel cotter pin makes an excellent pull pin) inserted in the eye passed through. A polypropylene loop attached to the eye of the pull pin was easily gripped by the ROV to release the restraint and allow the instrument to be picked up for use or deployment.

3.0 Payload Variations

3.1 Archaeological Sample Recovery

Archaeological sample recovery presents unique problems in that one is not absolutely certain of the weights or make up of materials you are attempting to recover (Figures [7], [9], [50] and [51]). It is important to work closely with the archaeologists to arrive at reasonable mass estimations. This approach enables the elevator design to accommodate the size and weight of the items you expect to recover. Most artifacts immersed in seawater for thousands of years are fragile so it also important to fabricate bins that cradle the artifacts and prevent unnecessary motion.

Figures [6] and [10] show an elevator used successfully in the Mediterranean. It was designed to lie flat on the bottom where large artifacts could be rolled into it if necessary. The netting was capable of stretching so that recovered items hung beneath the hard frame and served to cushion the contents upon recovery. The netting was standard polypropylene fish net (Figure [5]). It is easy to procure and reasonable in cost.

Figure [1] shows an elevator employed a few years later. It has the same flat frame with netting but with the addition of pockets and closable lids. The lids appear in a raised or ready position, being held up with pull pins. The pins will later be pulled at the bottom by the ROV after the elevator is full. The lids have been added to prevent lighter items from washing out when the elevator heaves in the waves on the surface. During artifact recoveries the rule is "think fragile".

3.2 Geological Sample Recovery

The types of geological samples that may be essential to science missions vary from soft sediment to hard rock and, on some occasions, all ranges of hardness in one lowering. An elevator with multiple compartments is normally required for such tasks. The elevator is deployed in a central area of interest and is used as a base station. As the ROV works the sampling area it can return to the elevator to swap out loaded sampling devices with empties, such as rock-filled baskets and trays of stuffed tube cores (Figure [26]).

3.3 Biological Sample Recovery

This sort of elevator is similar to those designed for geology. They are often the same shapes as geology baskets but with different bin styles meant to accommodate animals. Some bins and containers are supplied by scientists, and some are supplied or constructed at-sea by DSL personnel. It is not uncommon for scientists to use an elevator for geology (sulfides, water samples, chimneys, etc.) and biology (bio-mats, tubeworms, clams, shrimp, etc.) sampling on the same deployment, especially when working in a vent field. They repeat this combination sampling technique at each important vent area in order to obtain a complete picture of a particularly active area. While the ROV either stands by to continue sampling or moves off to survey a new vent site, a full elevator can be recycled to the surface, unloaded, reset and redeployed.

Figure [26] sequence: Jason pilot Will Sellers takes a benthic core sample and places it in a quiver for later offload to an elevator

4.0 Operational Considerations

4.1 Elevator Evolution

Current elevator design has evolved through three generations and was influenced primarily by recovery dynamics (Gleason 1999).

The first DSL elevator had much greater separation between payload and flotation, in fact the flotation was a separate fiberglass framework attached to the lower aluminum framework and basket by a taut cable (Figures [3] and [48]). There was no flotation attached to the basket frame other than the positive thirty-six pounds provided by the release transponder. This two-body arrangement kept the elevator bins twenty feet below the surface during recovery activities, well below any surface effects (Figures [17] and [18]). In 1989, this preliminary design successfully delivered forty-eight objects of antiquity to archaeologists and conservators without detectable damage.

The two-body elevator configuration, although very stable in the water column, introduced three serious operational concerns:

1. When the ROV worked at the basket it was directly beneath the cable and flotation frame. If the ROV were to lose power, it could rise up into the overhead hazard and become entangled. When moving the ROV near the elevator on the bottom, the pilot had to take extra precautions about multiple body positioning to be certain that the two-body elevator assembly, the ROV, and the ROV depressor were in a straight line with the ROV always in the middle.
2. Although well protected the samples were out of sight on the surface. This meant operators could not see if an object was about to wash out and be lost.
3. A problem was discovered during recoveries of the elevator by small boat in higher sea states. The dangling elevator created so much additional drag at the surface that forward way by the towing boat was severely diminished, making the operations overlong and dangerous. For these reasons and others DSL elevators are now single-body structures. (Two-body elevators are still used in concert with the manned deep submergence vehicle *Alvin*.)

In the second elevator iteration flotation was attached directly to the elevator frame comprising a single (stiffer) assembly. The frame was made as tall as possible and still be handled by the deck crane, about eight feet. This height kept the samples and equipment sufficiently below the surface but not as well as the first design. This new design also had the flotation clustered above and around a central frame. While this made ROV work less risky elevator towing dynamics during recoveries were poor. The basket was unstable on the surface, reducing small boat towing speeds and increasing sample exposure.

Figure [27] ROV Jason and Hiab knuckle-boom crane

Our most recent iteration (Figure [1]) shows a release transponder in the center of a horizontal column of flotation and a basket attached to either side. This is by far the best arrangement to date. It keeps the samples far enough below the surface but close enough for swimmers to help, if necessary, during recoveries. It also provides a favorable "fore and aft" arrangement for towing, meaning that the elevator clocks around behind the small boat and behaves well in higher sea states. A two point bridle is attached to one end at the base of the

floats that is easily pulled away from the frame by people in the recovery boat. A towline is then attached to the bridle apex for towing back to the ship. Tow speeds of two-three knots are possible without significantly tipping the elevator. This arrangement has the added advantage of allowing the recovery boat to work at two ends of the elevator without hovering directly over the sample baskets.

4.2 Deployment and Recovery

There are two critical moments in the life of an elevator event, deployment and recovery. During deployment it must survive being slapped into wave tops (sometimes repeatedly depending on sea state) without coming apart, breaking the anchor line or ejecting expensive instruments. During recovery a full elevator may spend as much as an hour bobbing up and down in swells. Even on a calm day an elevator can be very active on the surface. As a general rule, high-period sea states will make deployments difficult and low-period ground swells will make recoveries difficult. Experience has demonstrated that elevator deployments are much simpler than recoveries.

The DSL offshore operations group employs a portable, articulated "knuckle-boom" crane for the deployment and recovery of the ROV *Jason* (Figure [27]). This crane often performs the same tasks for elevators. A small boom winch on the crane is rigged with synthetic Spectra® lift line instead of wire rope because the torque-balanced weave of this line resists entanglement.

4.2.1 Deployment Procedures

Three qualified deckhands can deploy elevators anytime during day or night (Figures [1], [2], [28] and [29]). Deployments begin with the elevator secured to the deck or onto sawhorses by tie-downs. Those people on watch recheck to ensure that it has been properly tested and armed. A dive log entry is made. Two or more tag lines are drawn through the frame and doubled back so that one end can be slipped upon release and the tag kept aboard. The lift line of the crane will bear the load of the elevator as it is deployed. The bitter end has a ten-inch long eye spliced into it. The eye is wrapped around a load-bearing frame member at the top of the elevator, split and doubled back onto itself. A one-inch diameter by twelve-inch long stainless pin is inserted through the resultant "cat's cradle" (Figure [13]). The pin has another smaller line attached to the inboard end that is held lightly by a deckhand.

Figures [28] and [29] Nighttime and daytime deployments

Via handheld VHF radio the deck chief or boson asks the bridge for permission to deploy, and checks with the navigator to verify the vessel's position over the sample site. The ROV pilot is asked if the ROV and depressor vehicle (*Medea*) are safely out of the trajectory path of the elevator. The crane takes the load, tie-downs are removed, tags are controlled, and the elevator is lifted, swung overboard and lowered until it is awash. If satisfied, the deck chief signals for the stainless pin to be yanked from the cat's cradle, the lift line slips from around the frame and the elevator leaves the surface on a steady descent toward the bottom. The bridge is notified that the package is away and the navigator will begin to track its downward progress on the LBL display. A successful elevator deployment is logged and soon sampling can commence (Figure [30]).

4.2.2 Recovery Procedures

The recovery of an elevator, although reasonably straightforward, takes more coordination from those on watch and does have increased risk (Figures [1], [4] and [31]). Elevators are rarely recovered after dark. They can be equipped with relocation devices such as a radio frequency (RF) beacon and strobe, which are invaluable in low visibility or nighttime operations. The value of a fully loaded AVT is substantially more than the AVT itself (Figure [6]).

Figure [30] sequence: Approach, control, transport and placement

The watch officer or ROV pilot notifies the bridge officers and deck crew of a pending recovery. For most recoveries a small boat is made ready with a tow line (that can more than support the wet weight of the system) and launched prior to the release command being sent. The small boat crew will be responsible for towing the surfaced elevator back to the deck crane so they should be experienced and thoroughly briefed about recovery operations. Once all parties are agreed, the release code is sent by the navigator and logged. He or she tracks the elevator's progress toward the surface using the same onboard LBL transponder.

After an elevator has arrived on the surface it will float like an iceberg, only a fraction of

the overall structure will be visible, especially if it rises into surface glare, fog, darkness or has drifted down-current (Figure [31a-b]). The transponder will remain submerged inside the frame so some acoustic interrogation and ranging can continue. This is important when the system is not immediately visible and operators must estimate its location relative to the ship by LBL.

The small boat is piloted over to the surfaced elevator, a towline is attached and the elevator is carefully brought alongside to be hoisted aboard by the deck crane (Figure [31c-d]). The towline is passed to the deckhands and secured to the Spectra lift line. During the transition of the system from the surface to the deck it is imperative that people obey the deck chief's signals, that the load is controlled as well as humanly possible and that no samples are dislodged or damaged by the elevator's airborne movements (Figures [2], [4] and [31d]).

In some instances, such as in very good weather or in an emergency, the support vessel may maneuver alongside the elevator where the deck crew can attach a recovery lift line and tag lines by way of snap hooks and long poles. Bringing a large support vessel alongside a relatively flimsy, full elevator is not recommended, therefore the preferred method of recovery is through intervention by small boat. In either operational scenario, care must be taken to protect people first, samples second and equipment third.

4.3 Trimming an Elevator at the Surface

Before an elevator is deployed for the first time, as a matter of precaution, it is submerged at the surface and kept secured to the lift line. This operation is best executed in lower sea states. It allows time for engineers to observe the behavior and trim of the system, be certain that it is neither too heavy nor buoyant, and to adjust ballast and flotation calculations. An elevator seemingly ready for deployment but trimmed improperly could be too buoyant and drift quite a distance from its intended target, or it could be too heavily ballasted to recover any significant amount of samples (Figure [44]). It is worth noting that a well-balanced elevator on the bottom can be lifted and moved horizontally by *Jason* from one sample location to another, expanding the sampling range of a single elevator deployment.

Figures [32] and [33] Immediate conservation and sample documentation

4.4 Sample Handling and Conservation

After the system is aboard and secured, the deck crew should immediately step aside and allow qualified scientists to begin conserving the samples (Figures [32] and [33]). DSL members and ship's crews have never handled samples unless invited to by the resident conservator. Premature handling can contaminate the contents of the elevator and ruin sampling results. All crewmembers should be on alert for any unusual compounds on the deck or around the elevator station that might become sample contaminants (Sax 1974).

5.0 Elevator Navigation

Reliable and efficient deployment and recovery of elevators in deep water requires accurate navigation. An un-navigated elevator is easy to lose – both on the bottom and at the surface. Inertial navigation is impractical for elevators, and radio navigation signals (GPS, Loran) do not work under the ocean's surface. Acoustic navigation techniques are, at present, the only practical approach to navigating deeply submerged elevators. XYZ position sensing for elevators is usually achieved by long-baseline (LBL), short-baseline (SBL), or ultra-short baseline (USBL) navigation (Milne 1983).

Range, Depth and Altitude Acoustic Navigation. The simplest form of acoustic elevator navigation requires a battery-operated acoustic transponder on the elevator, a hull-mounted transducer on the surface ship, and a shipboard acoustic processing unit. With these instruments, and a sound velocity profile of the local water column, one can measure the elevator's range from ship, its depth, and altitude.

Ship to elevator acoustic range measurement (Figure [34]) proceeds as follows.

1. The ship board acoustic processing unit transducer sends an acoustic interrogation pulse from the hull mounted transducer on a specified frequency and/or code.
2. The elevator transponder detects the interrogation and responds with a specified reply pulse.
3. The ship board acoustic processing unit detects the reply pulse, and computes the round-trip travel time.
4. The ship board acoustic processing unit computes the elevator range (from the ship's transponder) using an average sound velocity estimate. Because range is not depth, range corrections using the full sound-velocity profile should be applied cautiously. Two additional acoustic returns will be generated by the above sequence.
5. Figure [35] depicts the direct "bottom bounce" return of the ship's interrogation pulse. The first bottom bounce return at this frequency/code can, with the sound velocity profile, be used to compute total water depth.

6. Figure [36] depicts the indirect “bottom bounce” return of the elevator transponder’s reply pulse. This return, together with the two returns mentioned previously, can be used to compute the elevator’s actual vertical depth, altitude, and horizontal range below the surface ship transponder. Corrections using the actual sound velocity profile can improve accuracy. This bottom bounce is typically the least reliable of the three returns described in this section.

A great variety of battery-operated acoustic transponders capable of interrogation-reply, acoustic payload release, and other functions, as well as shipboard acoustic processing units are commercially available. Several vendors are identified in Section 5.5.

Graphical Processing of Acoustic Returns: The technique of computing depth, range, and altitude with the sequence outlined above is not new – Oceanographers have been employing these techniques for decades. Initial implementations employed a calibrated electro-static strip-chart recorder to plot the acoustic returns graphically. The individual returns form well-defined lines on the strip-chart, making it easy to visually distinguish between the desired returns and spurious multi-path returns. This technique is perhaps most commonly employed when controlling the altitude of an oceanographic instrument lowered on a trawl wire. The difference between the transponder’s direct return and indirect return is easy to directly measure on the strip-chart. With the plot properly calibrated (based on sound-velocity and plotter pen-speed) it is easy to directly measure range, depth, and altitude. This approach remains a convenient and useful technique.

Computer Processing of Acoustic Returns: Computer processing can automate the computation of depth, range, and altitude data from the raw travel times. Computer processing of acoustic returns requires robust “flyer-filtering” algorithms to distinguish between correct returns (Figures [34-36]) and the numerous spurious indirect returns that are also received by the surface transducer (Milne 1983). Moreover, computer filtering algorithms typically require a human operator to “initialize the filter” by identifying a correct return. Recently reported results indicate success with automatic techniques for filter initialization (Yoerger, Bradley et al. 1999; Yoerger, Bradley et al. 2000).

5.1 Long Baseline Acoustic Navigation

Since its development over 30 years ago long baseline navigation (LBL) has become the de-facto standard technique for 3-dimensional acoustic navigation for full-ocean depth oceanographic instruments and vehicles (Hunt, Marquet et al. 1974). The de-facto standard method for full ocean depth XYZ acoustic navigation is 12 kHz long baseline (12 kHz LBL) acoustic navigation. 12 kHz LBL typically operates at up to 10 Km ranges with a range-dependent precision of ± 0.1 to 10 meters and update rates periods as long as 15 seconds (0.05 Hz) (Milne 1983).

Although recent work suggests that the next generation of acoustic communication networks might provide position estimation (Catipovic and Freitag 1990; Singh, Catipovic et al. 1996), no systems providing this capability are commercially available at present. All absolute acoustic navigation methods require exact knowledge of transponder location and are fundamentally limited by the speed of sound in water, about 1500 meters per second.

LBL operates on the principle that the straight-line distance between two points in the ocean can be measured by the time-of-flight of an acoustic signal propagating between the two points. All LBL systems require an unobstructed line-of-sight between transmitting and receiving transducers and, as mentioned above, have an effective range that varies with frequency.

The LBL description in this Section description is typical for 8-12 kHz LBL systems in deep water where ranges may vary from about 1 to 11 Km. The details of deployments may vary significantly for shallow water deployments, when operating over very short ranges, and when using high frequency LBL systems (100 kHz-1,000 kHz), but the essential steps of transponder placement, calibration, and operation still apply. As discussed previously, the precision and update rate of position fixes can vary over several orders of magnitude depending on the acoustic frequency, range, and acoustic path geometry. LBL navigation accuracy and precision can be improved to some extent by careful application of Kalman filtering techniques (Spindel, Porer et al. 1976; Bell, Howe et al. 1991).

Figure [40] depicts a typical oceanographic deployment of a 8-12 kHz LBL system for navigating an elevator. The remainder of this Section reviews how a typical LBL system is deployed and operated in deep water from a surface vessel.

5.1.1 Transponder Deployment

Two or more acoustic transponders are dropped over the side of the surface ship at locations selected to optimize the acoustic range and geometry of planned subsea operations. Each transponder is a complete sub-surface mooring comprised of an anchor, a tether, and a buoyant battery-powered acoustic transponder. The tether's length determines the transponder's altitude above the sea floor. Depending on range, local terrain, depth, and other factors, tether length might be chosen between 5 and 500 meters.

The simplest transponders are designed to listen for acoustic interrogation "pings" on a specified frequency (e.g. 9 kHz), and to respond to each interrogation with a reply ping on a specified frequency (e.g. 10 kHz). It is common (but not universal) to set an entire network of transponders to listen on a single frequency, and to set each transponder to respond on a unique frequency.

5.1.2 Sound-Velocity Profile

Sound velocity typically varies significantly with depth. Acoustic navigation can employ a sound velocity profile to compensate for the effects of variation in sound velocity. Sound velocity profiles are typically obtained by lowering an instrument from the surface ship to measure and tabulate various physical characteristics. The most commonly available "CTD" probes measure three quantities – conductivity, temperature, and depth. From these variables, sound velocity can be computed directly as

$$c = 1449.2 + (4.6 t) - (0.055 t^2) + (0.00029 t^3) + ((1.34 - (0.01 t)) (s - 35)) + (0.016 d)$$

where c is sound velocity in meters/sec, t is water temperature in degrees centigrade, s is salinity in parts-per-thousand, and d is depth in meters (Ulrick 1983).

For example: The sound velocity profile used in the calibration and operation of an LBL transponder network in June 1994. The authors and collaborators obtained this sound velocity profile in June 1994 at 28°N 44°W (Whitcomb and Crook 1994). A temperature profile taken with an CTD probe in the center of the network at 18:00 UTC on 26 June 1994 provided a temperature

profile from 0 to 760 meters. The WHOI CTD Group generously provided historical data for the temperature profile below 760 meters, and for the entire salinity profile. A computer program (PHYPROPS.FOR version September 28 1983 by N. Fofnoff and R. Millard of the WHOI CTD Group) was used to compute the sound velocity profile from this data. Figure [38] shows the resulting sound velocity table, and Figure [37] shows a plot of the sound velocity as a function of depth.

5.1.3 Transponder Survey

The XYZ position of the sea-floor transponders is determined by maneuvering the surface ship around each transponder location while simultaneously (a) acoustically interrogating the transponder and recording the round-trip acoustic travel time between the ship's transducer and the sea-floor transponder and (b) recording the ship's GPS position, compass heading, and velocity. This data is processed to compute least-square estimate of the world-referenced XYZ position of each fixed sea-floor transponder. When using a full-precision P-Code GPS, the transponder's position can typically be estimated with a precision of just a few meters.

Figures [39a-d] show an example of a transponder survey performed in aboard the *RV Knorr* by the authors and collaborators from 04:15 to 06:23 UTC on 8 July 1994 at 28°N 44°W. In this survey, a Benthos TR6000 transponder was moored at approximately 3000 meters depth. The survey obtained a total of 678 individual ship to transponder round-trip travel times. The ship to transponder round-trip travel times were obtained using a Benthos 455 Acoustic Signal Processor. The travel times are corrected for the effect of ship velocity and logged by the DSL_NAV program written by S. Gegg at WHOI in the C programming language. The *Knorr's* location during the survey was measured with its WRN6 P-Code military GPS receiver. The *Knorr's* heading was measured with its #1 gyro, a Sperry MK-37 Gyrocompass. The magnetic variation at the TAG site is 18° W.

DEPTH	SOUND VELOCITY
1	1537.94
5	1538.35
10	1538.19
19.9	1538.1
29.9	1535.06
49.9	1531.59
74.8	1531.29
86	1531.45
99.7	1530.45
124.5	1529.52
149.4	1527.61
199.2	1523.11
248.9	1521.6
298.6	1520.42
397.9	1515.9
497.2	1511.66
596.5	1508.42
695.6	1503.28
760	1501.6
794.7	1500.05
893.8	1497.55
992.8	1495.27
1091.7	1494.37
1190.6	1493.67
1289.4	1494.04
1388.2	1494.71
1486.9	1495.26
1733.6	1496.83
1979.9	1499.13
2225.9	1501.08
2471.6	1504.17
2717.1	1507.22
2962.3	1511.24
3207.2	1515.11
3451.9	1519.33
3601.4	1521.96
4000	1528.8

**Figure [38] Typical sound velocity profile data –
June 1994, 28°N 44°W**

The ship's position during survey operations was measured using a WRN6 P-Code GPS unit on loan from the U.S. Navy. We are grateful to the U.S. Navy for their generous efforts in providing and supporting this highly accurate navigation instrument. The availability of this P-Code GPS unit in surveying and DP operations enables ship and, in consequence, LBL vehicle navigation previously unattainable in the open ocean. It has proven to be an invaluable scientific asset.

The estimated position of each transponder was computed using the GPSCAL2 computer program written by Dr. D. Yoerger at WHOI/DSL in the MATLAB programming language. His computation uses the following information:

- (a) ship-to-transponder travel times,
- (b) corresponding ship positions, headings, and sensor locations,
- (c) nominal planned transponder depth, and
- (d) the sound velocity profile.

The transponder position was estimated as follows:

1. A ship-to-transponder range is computed for each round-trip travel time. This range is computed using the sound-velocity profile shown in Figure [37] and the nominal planned transponder depth.
2. The individual ranges are manually filtered to discard outlying returns.
3. The transponder position is estimated.
4. This position provides the best fit (in a least-squares sense) to the observed ranges.
5. The effects of ship heading and hull mounted sensor locations are compensated.
6. The root mean squared (RMS) fit error is computed. The RMS fit error is the square root of the sum of the difference between (a) the observed ship-transponder range and (b) the computed range between the known ship's position and the estimated transponder position. As will be seen in the sequel, this RMS error is only a partial measure of the accuracy of the estimated transponder position.

5.1.4 Acoustic Navigation of Surface Ship Position

First, the ship's acoustic signal processing computer transmits an interrogation ping via the ship's LBL transducer on a common interrogation frequency, say 9.0 kHz.

Second, each of the fixed sea-floor transponders replies with a ping on a unique frequency that is received by the ship's LBL transducer. The ship's computer measures the round-trip travel acoustic travel time between the ship's transducer and to two (or more) sea-floor transponders. Finally, the ship's computer computes the absolute ship position using (a) two (or more) measured round-trip travel times, (b) the known depth of the ship's transducer, (c) the surveyed XYZ position of the sea-floor transponders, and (c) the measured sound-velocity profile.

Figure [39b] Typical transponder survey: ship positions and estimated transponder position using raw residuals

Figure [39c] Typical transponder survey: ship positions and estimated transponder position after manually filtering returns

5.1.5 Acoustic Navigation of Elevator Position

The following method is used to determine the position of an elevator, underwater vehicle, or instrument from the surface ship:

1. The ship's acoustic signal processing computer transmits an interrogation ping via the ship's LBL transducer on special interrogation frequency, say 8.5 kHz (Figure [40]).
2. The elevator's transponder responds to the ship's interrogation by generating a ping on a secondary interrogation frequency, say 9.0 kHz (Figure [41]).
3. Each of the fixed sea-floor transponders replies to the secondary interrogation by generating a ping on a unique frequency that is received by the ship's LBL transducer (Figure [42]).
4. The ship's computer measures both the direct round-trip acoustic travel time between the ship's transducer and the vehicle and the indirect round-trip travel time from ship to vehicle to transponder to ship for two (or more) sea-floor transponders. Finally, the ship's computer computes the absolute ship position using (a) the measured round-trip travel times, (b) the known depth of the ship's transducer, (c) the surveyed XYZ position of the sea-floor transponders, and (d) the measured sound-velocity profile. In the case of tethered underwater robot vehicles, the known depth of the vehicle (obtained from an on-board pressure sensor) is often used in the position computation.

5.1.6 Transponder Recovery

Most sea-floor acoustic transponders are equipped with an acoustically triggered device which releases the mooring tether in response to a coded acoustic release signal, thus allowing the transponder to float freely to the surface for recovery. In most oceanographic deployments the transponders are triggered, released, and recovered at the conclusion of operations.

Figure [42] Step 3 of LBL cycle: Each of several fixed seafloor transponders responds to a 9.0 kHz elevator transponder ping signal with an acoustic ping at a unique frequency

5.2 Short Baseline and Ultra-Short Baseline Acoustic Navigation

Short-baseline (SBL) and ultra-short baseline (USBL) acoustic navigation systems offer an alternative to LBL systems for 3-D underwater acoustic positioning. These systems employ an array of three or more transponders mounted in a known configuration of a surface ship's hull. The systems determine the range of a submerged transponder by the round-trip travel time of an acoustic signal (Figure [43]) (Morgan 1978). In addition, SBL and USBL systems also measure the relative phase of the transponder's response pulse to determine the angular azimuth and angular altitude of the transponder's position with respect to the surface ship. The range, angular azimuth, and angular altitude of the transponder completely specifies the transponder's position in polar coordinates with respect to the surface ship. In addition, many SBL and USBL systems can use the ship's real-time heading, attitude, and position to compute the transponder coordinates in world coordinates.

SBL and USBL systems offer the significant advantage of requiring no LBL transponder network deployment or calibration. The author's experience is that SBL and USBL systems provide unequalled ease of deployment, but to date we have not observed SBL and USBL systems to provide the same level of navigation consistency and accuracy obtained by LBL systems when operated in deep water. As with all acoustic navigation systems, SBL and USBL system performance depends on depth, range, thermal and salinity profiles, ambient noise, and a variety of other factors. Several commercial vendors of these systems are listed in Section 5.5.

5.3 Finding the Elevator on the Bottom

The ROV pilot and navigator work together to locate an elevator once it has reached the bottom. If the elevator has drifted more than 150 meters away from the ROV, the pilot maintains ROV control at a safe altitude above the bottom (2-5 meters) while the navigator provides the pilot with LBL range and bearing to the elevator. When comfortable about ROV position, the pilot

asks the navigator to maneuver the ship and ROV system toward the elevator. The pilot may allow the ROV to be towed or he/she may choose to actively fly on the correct bearing. Ranges begin to decrease during either kind of approach. In the case of *Jason* operations, ranges are the distance between the elevator and a wire-mounted LBL relay transponder above *Medea* or an LBL transponder directly onboard *Medea* or *Jason*.

As the two bodies close on the elevator (<150 meters) the pilot completes the approach using scanning sonar and finally the ROV's forward-looking video cameras. The navigator and winch operator center up the *Medea* vehicle about 5 meters above *Jason*, which is above the elevator. This prevents fouling by the three. When the elevator comes into view it is inspected for damage and may be moved by the ROV to a more ideal location closer to the sampling site.

5.4 Elevator Navigation Do and Don't List

1. Do carefully determine and log the release position, time, wind conditions, surface current profile (if available) descent rate, and X-Y set of each elevator drop. Use this information to refine the release point position for subsequent elevator drops.
2. Do log all descent data, including bottom location and time.
3. The second most dangerous navigation moment in elevator operations occurs when you have sent the acoustic release code. You first must determine if the release code has been received by the elevator transponder – most release beacons send a confirmation signal to indicate receipt of a release code. You then must track the elevator position and depth to determine if the descent weight has been released, if the elevator is ascending. If the elevator is ascending, you must determine the ETA on surface and expected position relative to the surface ship. Refine and verify the estimate during ascent.
4. Do log all ascent data.

5. The most dangerous navigation moment in elevator operations occurs when the elevator is on the surface. The acoustic transponder is often awash, and further acoustic navigation may be impossible.
6. Do have an "elevator lost at surface" plan in place, and any necessary data and equipment on hand. What is the color and repetition rate of the strobe? Battery life? What is the frequency and code of the RF beacon? Battery life? Where is the RF direction finder unit? When was it last tested?
7. Do give the bridge several hours of advanced warning in advance of any elevator deployment or recovery.
8. If a small-boat operation is anticipated, do brief the bridge, the small-boat crew and deck chief on the expected operation (see Section 4.2).
9. Do communicate effectively with the ship's bridge during deployment and recovery.
10. Do communicate to the bridge at the conclusion of all elevator operations.
11. Do respect the bridge's protocol for communicating with the small-boat and crane.
12. Do not recover elevators at dusk, at night or in the fog.

5.5 Commercial Acoustic Navigation System Vendors

1. Benthos Inc., 49 Edgerton Drive, North Falmouth, MA 02556 USA, phone: 508-563-1000, fax: 508-563-6444, URL: <http://www.benthos.com>.
2. Imetrix Inc., 1235 Route 28A, P.O. Box 152, Cataumet, MA 02534-0152 USA, phone: 508-564-6460, fax: 508-564-6860, URL: <http://www.imetrix.com>.
3. Sonardyne International Ltd, Ocean House, Blackbushe Business Park, Yateley, Hampshire, GU46 6GD, UK. phone: +44 (0)1252 872288, fax: +44 (0)1252 876100, URL: <http://www.sonardyne.com>.
4. Racal Pelagos, Inc., 5434 Ruffin Road, San Diego, California, 92123, USA, phone: 858 292 8922, fax: 858 292 5308, URL: <http://www.pelagos.com>.
5. Nautronix Ltd (Head Office), 108 Marine Tce, Fremantle, Western Australia, 6160, phone: +61 8 9430 5900, fax: +61 8 9430 5901, URL: <http://www.nautronix.com>.
6. Kongsberg Simrad AS, P.O. Box 483, 3601 Kongsberg, Norway, phone: 47 32 28 50 00, fax : 47 32 73 59 87, URL: <http://www.simrad.com>.
7. ORE Offshore Division, 10450 Stancliff, Suite 115. Houston, Texas 77099, phone: (281) 879-7277, fax: (281) 879-9213, URL: <http://www.ore.com>.

Figure [44] Portion of DSL ballast and flotation spreadsheet

ROV / ELEVATOR PAYLOAD WORKSHEET									
ELEVATOR 01								MFB	#####
FILL IN THE YELLOW CELLS ONLY									

6.0 Ballast and Flotation Spreadsheet

6.1 Introduction and Layout

The ROV *Jason* and its array of sample elevators provide a service to the science community (Bowen, Fornari et al. 1993). Artifact elevators typically have less instrumentation than biological or geological elevators (Figures [2] and [20]). ROVs can support a wide variety of temporary sensors and tools. As cruise goals change, DSL works to adapt the system for new and unusual sampling devices. Ballast and flotation records are crucial when dives involve previously unknown sampling and sensor suites. Over time, DSL has accrued information that describes the specific gravity (density or displacement in freshwater and/or seawater) of materials and components that are often assembled to customize an elevator or that will affect an ROV's ascent/descent trim.

A simple spreadsheet can help ROV and elevator operators determine how effective a deployment will be. A spreadsheet template is provided with this report (Figure [44] and [CDROM]). The spreadsheet is constantly changing and can apply to either system. It is only a guide to trimming, not the answer. Resulting calculations should be adjusted according to elevator trimming exercises alongside the support vessel. A single flooded housing ignored at the surface could mean a lost elevator later in the sampling operation. A poorly trimmed ROV will waste energy holding station at depth, and perhaps cause damage to a vulnerable site.

Columns A-B of the included spreadsheet categorize subsystems that may be aboard the ROV or AVT to be deployed. Major subsystems mentioned: Materials (raw stock, pure samples, elements); Components (commonly included subassemblies); Devices (portable instruments added to or removed from either elevator or ROV); Ballast (portable and not), and Flotation (none releasable). Subtotals will reveal whether or not the ROV or elevator is skewed in trim. The negative or ballast influences are highlighted in red, the positive or flotation are in blue. Offload devices have green cells. Yellow cells are for user entries on a case-by-case basis. The template is meant to be cleared prior to any new deployment. Start from scratch and pay attention to detail.

6.2 Spreadsheet Displacement Factors

The displacement of elevator components can be determined by various methods. After years of deployments, DSL engineers have found that the most reliable data is obtained by submerging a component or subsystem in seawater and deriving the local specific gravity (air mass / volume in cuft x 64 pounds per cuft = specific gravity in seawater; air mass / volume x 60 pounds per cuft = specific gravity in freshwater). Column G is a field-derived conversion factor for each item. The factor is checked against known specific gravity data, however an onboard measurement precludes the printed information.

DSL operations specialists understand that a true volume of an assembled component is difficult to measure. Instead of attempting to dissect volumes from a complex device, operators fill a fifty-five gallon drum with on-site seawater and verify the specific gravity of each elevator component. Using a precision scale (+/-0.5 pounds) each subassembly is weighed in air and then weighed in the filled drum. The difference is the displacement in the local seawater and that number is entered into the spreadsheet. By this method the ballast and flotation calculations provide accurate results for the environment at that particular site and time.

6.3 Guidelines for Vertical Velocities

The bottom line (Subtotals) of the ballast and flotation spreadsheet gives operators an idea of how well the autonomous system will sink upon deployment and float after release. A well-ballasted elevator will float to the bottom to a location close to the benthic worksite as estimated by the navigator. An elevator filled with samples will rise to the surface in the vicinity of the support vessel. Future elevator designs may incorporate steerable features.

Depending on the framework shape of an elevator (more or less drag) the desired ascent/descent rates are on the order of thirty to ninety feet per minute. Sixty feet per minute is

an ideal rate for elevators described in this report. A ninety feet per minute ascent rate is extreme and can disturb and disperse valuable samples into the water column; and an empty elevator may arrive at the surface. If the ascent rate is less than thirty feet per minute, there is a danger that the entire elevator will be transported down current a significant distance before recovery can be initiated.

The Subtotals section of the spreadsheet reveals to the operator how an elevator will behave in the water column. The TOTAL IN-AIR WEIGHT is the first summation, which is the expected weight of the entire system when deployed. The deployment crane should be checked to ensure that the elevator can be handled safely. Most DSL elevators have a dry weight of 800 to 1,500 pounds.

The TOTAL IN-WATER WEIGHT is a summation of all sinking masses. The TOTAL FLOTATION ABOARD summation includes all components buoyant and neutrally buoyant. The ON-BOTTOM WEIGHT is the elevator mass prior to any off-load packages being deployed. AFTER EXACT REMOVED subtracts the ballast defined by the two offload units. AFTER ANCHOR DROPPED is the ascent buoyancy without sample masses. If this value is overwhelmed by ROV samples introduced to the elevator, it will not reach the surface.

A well-arranged elevator will sink or rise with 75 to 120 pounds of influence. This is a statistic borne from DSL experience only. In the included example the data suggests that the elevator was delivering Exact Transceivers. It was 210 pounds negative on the bottom and had the potential to be 63 pounds buoyant upon release. This means that few samples could be added to the elevator or there was a risk it would not rise directly. If a smaller offload package had been proposed more samples could have been recovered on this deployment.

7.0 Specialized ROV Manipulator End Effectors and Articulated Scoops

Two principal ROV-borne tools that are used to perform sampling tasks in concert with elevators are called mitts and scoops. Smaller samples, such as oil lamps, wooden objects and

Figure [45] Jason mitts on manipulator and an articulated scoop

medium-sized earthenware have been recovered with a compliant pair of mitts (Figures [7], [8] and [36]). Larger samples (encountered by DSL) to date, such as amphorae and grinding stones have been recovered using a hydraulically actuated, articulated scoop (Figures [45] and [49]).

Artifacts have ranged in mass from a few ounces to seventy-five pounds in water, in age from the 1st Century AD to 2,700 BCE (Figure [5]). Mosaicked survey imagery taken by *Jason* helps professional archaeologists and conservators predetermine exactly which artifacts are important to their studies. Every candidate sample is thoroughly mapped and scrutinized prior to contact by the ROV's tools. Archaeological requirements and crucial operating parameters guide engineers and technicians in their efforts to modify and improve both sampling systems in the field. Operational parameters include sample robustness, bottom sediment type, degree of sample burial, local currents, ROV pilot skillsets and manipulator condition.

After collection by mitts or a scoop, artifact samples are transported away from the site and over the ocean floor by *Jason* and offloaded into numbered elevator baskets and bins. Sampling can continue while the elevator cycles a sample payload to the surface. Meanwhile other samples are carefully cached by the ROV near the worksite in preparation for the next (empty) elevator's arrival.

Figures [46] and [47] Two versions of manipulator end effector mitts

7.1 Materials and Construction Practices

7.1.1 Manipulator Mitts

Mitts are made of threaded 300 series stainless steel rod, 6061-T6-aluminum stock in various forms, neutrally buoyant poly-plastics, polyurethane and Tygon[®] tubing, synthetic netting in various mesh sizes, six-thread hemp, waxed or unwaxed whipping twines, ScotchKote[®] insulating adhesive, Tytraps[®] and stainless steel hose clamps. DSL operators always bring these raw materials into the field. A finished mitt pair is usually spray-painted with Krylon[®] flat black to reduce the reflection of artificial light back into *Jason*'s cameras. Conservators have not identified these materials as sample contaminants as long as they are fully cured before diving begins.

Mitts design and applications have changed over the years (Figures [46] and [47]). No drawings of these specialized devices currently exist. Because the standard manipulator end effector, or gripper, is occasionally needed for non-sampling ROV dives, the mitts must not replace the gripper but attach to it as a readily removable extension. Attachment to the paired gripper jaws also allows the clamping action of the gripper to actuate the mitt halves.

7.1.2 Articulated Scoops

Scoops are constructed of materials similar to those described above for mitts (Dexter 1985). They are mounted to the leading edge of the ROV's sample platform, also known as the

front porch. Since the sample to be recovered by a vehicle scoop is normally larger or more massive than those recovered by mitts, scoops are stiffer and slightly less compliant. Scoops appear like a combination of elephant tusks and a cowcatcher (Figure [49]). The operational theory is that if the device can carefully penetrate the substrate supporting the artifact, it can capture and carry the same without degrading sample value. DSL scoops often collect a layer of substrate, which cushions a sample during transport to an elevator.

Figure [48] Denzel Gleason checks a preliminary scoop design

Actuation (closure) of a scoop is accomplished by an auxiliary hydraulic system aboard the ROV. The actuator opens and closes the top half. The actuator piston is linked to an over-center lever-arm on the scoop's upper half (Figure [49]) (Shigley, Mischke 1989). The lower half is passive, yet it is also hinged and can pivot against the front porch as the ROV changes vertical position. This flexibility allows a pilot to approach a large artifact and gently rock it into the scoop, then determine whether it is safe to clamp the upper half down over the sample. Successful clamping allows transport of the artifact but only occurs after clearance by the expedition archaeologist.

7.2 Results and Recommendations

7.2.1 Manipulator Mitts

Mitts have been proven to be effective non-destructive sampling tools on four expeditions to the Mediterranean Sea. Archaeologists have permitted the use of mitts for the recoveries of over three hundred artifacts since 1989. All recoveries are initiated from well below the limits of safe SCUBA diving depths of 150-200 feet, further demonstrating the value of precise, remote-controlled sampling techniques (Figures [50] and [51]). As the design of mitts has progressed, DSL operators found that it was important for the two halves to be unequal in stiffness (Figure [8]). This allows one pair of mitts to adjust to sediment conditions and the resting attitude of a wide range of smaller artifacts.

In future expeditions, it has become apparent that excavation of sediment will be required in order to expose lower layers of a site. Suction pumps, Venturi lifts and other active devices may be brought to bear as archaeologists expand their acceptance of ROV remote sensing and remote-controlled sampling techniques. Engineers will likely redesign the existing mitts so that

new demands by experts are attained. The mitts described here are rudimentary, are successful, but are not necessarily the most sophisticated application of a modified manipulator end effector.

7.2.2 Articulated Scoops

Scoops are less developed than mitts. When first employed in expeditions between 1989 and 1993, the design was experimental in nature and required a certain diligence on the part of ROV pilots to fulfill the requirements of archaeologists and ensure that precious artifacts would be transported with the utmost, undetectable care. Having no reference, pilots walked through the new sampling procedures in simulations and later perform sampling tasks with the same experts present in the topside control area.

The largest and most common artifact class recovered by *Jason's* scoop is an ancient container known as an amphora (Figure [5]). Amphorae have ranged in age, mass, wall thickness, contents and brittleness. DSL engineers have modified the scoop's clamping forces according to amphora parameters recorded by divers who have recovered them from coastal waters. The present hydraulic ram, which allows the ROV to capture and lift an amphora, often appears under-powered, however it is evident that in many cases a more powerful clamping force could very well have damaged or destroyed a sample. The current DSL scoop actuator has been successful in retrieving dozens of large amphorae even though it requires the pilot to work harder at ROV control, ROV approach and eventual artifact possession (Figures [9] and [30]). Any advances in scoop clamping power should be tested prior to field application.

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Figure [50] sequence: Jason mitt's recovery of ancient bowl by selection, envelopment, transport, placement and conservation

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Figure [51] sequence: Jason mitt's recovery of ancient jar by envelopment, transport, position and placement