Pressure-Controlled Excavation Technology for Contaminated Sediment Removal

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Pressure-Controlled Excavation Technology for Contaminated Sediment Removal

Final Report

Prepared for the

New York State Energy Research and Development Authority

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ABSTRACT

This report describes the results of a research and development effort to develop an advanced, more efficient excavator for the removal of subaqueous contaminated sediment. The technology employs a concept that is similar to that of a simple diving bell in which air pressure is controlled within an enclosure to permit an excavation bucket to be lowered to the bottom of a waterway and excavate sediments in a water-free environment. This prevents the mixing of contaminated sediments and the water column during the dredging-excavation process. Air pressure within the enclosure can be lowered during the excavation in order to collect loose sediment that would typically migrate from the site. Such a system has the potential for mitigating problems associated with dispersion of contaminated sediments into the water column, lowering levels of residual contamination left behind during the dredging process and reducing the moisture content of sediments extracted during the excavation process.

Keywords

Subaqueous contaminated sediment
Cleanup
Remediation
Dredging
Residual contamination

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SUMMARY

In recent years, the ecological impacts associated with the presence of subaqueous contaminated sediments in our nation's waterways have resulted in regulatory and in some cases enforcement actions by Federal, state, and local authorities to remediate the problem. Planners and engineers responsible for designing remediation strategies for such contaminated sites have a limited number of options from which to choose. The primary options available fall under the categories of 1) natural attenuation, 2) sediment removal, and 3) in-situ management.

Natural attenuation is a passive strategy that permits natural processes to degrade or disperse the contamination present in the sediment. Sediment removal is an active strategy that involves extracting the contaminated sediment from the bottom of the waterway and disposing of the sediment at a secure location. In-situ management is an active strategy that does not include sediment removal. It includes sediment isolation and/or in-situ treatment. Sediment isolation typically involves sediment capping, which is a strategy that is designed to separate the contaminated sediment from the sediment-water interface. The sediment-water interface is an active biotic zone (i.e., an eco-sensitive area in the waterway) and is the location where sediment-water interface transfer actively occurs. Capping the sediment-water interface can prevent the transfer of contaminants into the active sediment biotic zone where it can be transferred to organisms in the food chain or dispersed into the water column. In-situ treatment is a strategy that is designed to treat the sediments in-place through the addition of reagents that can enhance the degradation or fixation of contaminants present in the sediment through microbial or chemical reactions.

In those instances where direct impacts to fish and wildlife have been linked through processes of food-chain transfer and bioaccumulation of contaminants present in the sediment, sediment removal is typically chosen as the primary remediation strategy. Sediment removal in almost all cases employs "conventional dredging technology" to remove the effected sediment. Conventional dredging technology makes direct use of equipment and operations that were developed to provide for navigation-dredging (i.e., the removal of sediments for the purpose of deepening navigational channels). The basic technology employs one of two general approaches: 1) mechanical dredging, or 2) hydraulic dredging. Mechanical dredging makes use of clamshell buckets to scoop out and remove the sediment. Hydraulic dredging removes sediment by agitating the bottom of the waterway and vacuuming the dislodged sediment particles. More detailed discussion of conventional dredging technology is presented in Section 2 of the main body of the report. While conventional dredging technology is well suited for the mass removal of sediment to deepen channels, it has major limitations as a contaminated sediment removal technology.

During conventional dredging operations, the digging and raking action of dredging equipment will destabilize the sediments located at the sediment-water interface. When sediments are destabilized, they are no longer bound to the bottom of the waterway. This is a particular problem when lighter (i.e., low

specific gravity) particles are destabilized. These particles are susceptible to dispersion and readily move with the prevailing tide or current. The distance that they migrate is a function of the specific gravity of the particle and the velocity of the prevailing currents. Eventually most particulate matter resettles to the sediment-water interface either recontaminating the remediated area or contaminating a new location(s). The degree of contamination at these secondary locations is dependent on the amount of sediment dispersed and the level of contamination in the sediment. Paradoxically, the lighter weight sediment particles, which tend to be most susceptible to destabilization, tend to be organic and hydrophopic in nature, and also contain the highest levels of contamination.

In most contaminated sediment waterways, sediments with higher levels of contamination are typically located below the sediment-water interface. This is because such sediments were most likely deposited decades ago and have since been silted over. During dredging activities, these sediments will be mixed with overlying silts and transferred to the sediment-water interface, recontaminating the surface layer (i.e., the sediment water interface layer).

While it is generally acknowledged that the negative short-term effects of dredging will be more severe than simply leaving the contaminated sediments in place (i.e., natural attenuation), recent data also suggest that the positive long-term effects of conventional dredging technology may be less than anticipated. This is because the mixing and dispersion of sediments and the inefficiencies of conventional dredging operations leaves levels of residual contamination behind which, for many contaminants, will exceed the desired target cleanup level.

The result is that there is a pressing need for the development and demonstration of new approaches and technologies to provide improved excavation tools that capture and prevent the migration of sediments destabilized in the dredging process and minimize the negative effects of residual contamination left behind in the dredging process. This report describes the results of a research effort designed to introduce such an approach. The technology under development is referred to as Pressure-Controlled Excavation Technology. The technology was developed by a team of engineers and scientists under contract with the New York State Research and Development Authority, the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), and the National Oceanic and Atmospheric Administration (NOAA).

Pressure-Controlled Excavation is designed to provide for the collection of sediments using a mechanical bucket that is contained within a specially designed, pressure-controlled enclosure. A design (isometric) drawing of such an enclosure is shown in Figure S-1. Photographs of the field prototype unit descending into the water during an excavation test are shown in Figures S-2 and S-3.

In the Pressure-Controlled Excavation process, the pressure within the enclosure is adjusted to control the water level inside the enclosure during dredging operations. Controlling the water level inside the enclosure provides the means to collect destabilized particles during the dredging process, before they can migrate from the dredge site. This is accomplished by pressurizing the enclosure, and lowering the enclosure and bucket to the sediment-water interface. Sufficient pressure is provided during descent to prevent a rise of water level into the enclosure. During the excavation process the pressure in the enclosure is reduced and the water is permitted to rise into the enclosure. As water rises into the low-pressure enclosure, the dispersed particles are drawn into the enclosure, minimizing the loss of dispersed sediment particles during the excavation. Employing this alternating cycle of positive and negative pressure during descent, excavation and ascent provides the means to collect destabilized particles. Destabilized sediment particles collected during this operation are pumped to a small water treatment facility to remove the collected particles so that the pumped water can be safely returned to the waterway.

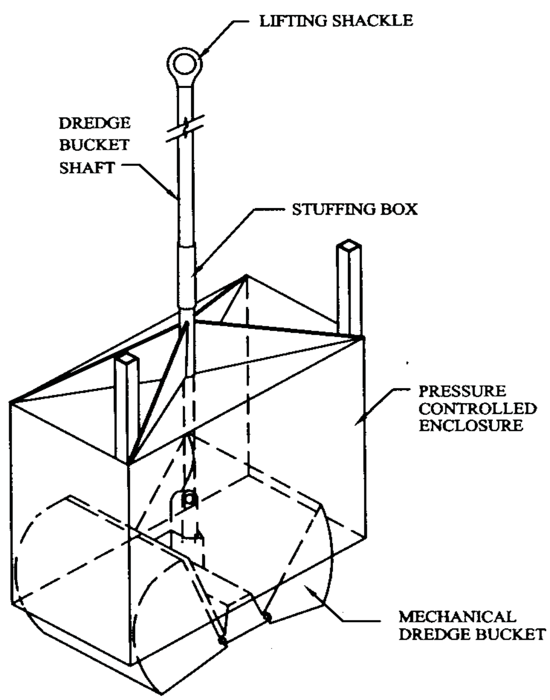

Figure S-1: Pressure-Controlled Enclosure and Bucket

The research effort described in this report included the design and construction of a small bench unit, and the design and construction of a field prototype that was subjected to a series of tank tests and field trials. The results of the research effort to-date suggest that control over the dredging process is feasible using Pressure-Controlled Excavation Technology. Additional work is required however, to provide improved feedback-control sensitivity to the pressure changes that are encountered within the enclosure during dredging operations.

Pressure-Controlled Excavation Technology is being developed by Seaway Environmental Technologies (www.seawaytech.com).

Figure S-2: Pressure-Controlled Excavator Ready for Submersion

Figure S-3: Pressure-Controlled Excavator Descending Below Surface for Excavation

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Section 1

BACKGROUND

A large part of the dredging process problem results from the fact that current dredging technology destabilizes subaqueous sediments. This is due to the digging and raking action of the equipment used in the excavation process. Sediment stability is a measure of the resistance of sediments to the abiotic and biotic forces that promote sediment transport. As a result, destabilization of the bottom sediments means that the sediments, particularly those present at the sediment-water interface, no longer exhibit this stability.

Destabilization of subaqueous sediments during dredging operations is initiated by the digging process, when the side walls of the excavated trench collapse into the excavated hole and sediment particles disperse into the water column. Lighter (i.e., low specific gravity) particles tend to migrate from the immediate dredge area with the prevailing currents. Many of these lighter particles can resettle in quiescent zones or combine (coagulate) with other particles and resettle to the bottom of the waterway downgradient from the dredge area. Most of the heavier particles (i.e., high specific gravity) resettle rapidly. Many of the lighter coagulating particles form a floc that may reenter the sediment bed, or hover near the sediment-water interface in a layer of elevated suspended solids. The existence of this high suspended solids or fluff layer is well known and was documented in a National Research Council report as far back as 1987 (National Research Council, 1987).

From an environmental perspective, this fluff layer is typically made-up of low-density organic rich sediment particles. These particles will tend to be higher in levels of hydrophobic contaminants, such as PCBs, than heavier sediment particles. The presence of this contaminated fluff layer at the sediment-water interface is further troubling, since it interacts directly with the active biotic zone and can continue to impact the subaqueous ecosystem long after dredging is complete. During dredging operations, attempts to capture this fluff layer have met with marginal success. The presence of such a layer ultimately limits the overall efficiency of a sediment cleanup.

While the aforementioned considerations are recognized as dredge-limiting problems, the development of new approaches to mitigate these issues has received little attention. The development of new technology and particularly the development of "new remediation equipment technology" in the field of contaminated sediment remediation have been painstakingly slow. This is because research in this area requires the development and use of heavy equipment, which can rarely be conducted in a university setting where most research activity is centered. Few dredging contractors have the resources to undertake research activities or engage in the development of new equipment, and government agencies have been slow to respond to the residual contamination issues and to provide resources to investigate new remediation strategies. Most of the new excavation technology that has been under development has been undertaken in foreign countries and has not received significant attention in the United States (Cleland, 1997). Existing contaminated sediment dredging practices (i.e., with clamshell buckets and hydraulic dredges) are basically the same methods that have been used for navigational and maintenance dredging for decades.

This report provides a description of the development of a new excavation technology designed to provide improved cleanup operations for contaminated sediments. The technology developed is referred to as Pressure-Controlled Excavation Technology. Its primary purpose is to collect, during dredging operations, the sediments destabilized during this process. Collection of such sediments would mitigate contaminant dispersion problems and improve the efficiency of the waterway cleanup. Support for the development of the technology was provided by the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), the National Oceanic and Atmospheric Administration (NOAA), the New York State Energy Research and Development Authority, Cornell Cooperative Extension of Suffolk County, Marine Division, and the Pall Corporation of East Hills, NY. The technology was developed by Chesner Engineering, P.C. and Melrose Marine Service, Inc. It is described in detail in two U.S. Patents[1] and is being marketed under a third party company, Seaway Environmental Technologies, Inc.

The report is divided into five subsequent sections that provide an overview of current dredging technologies (Section 2), a description of how Pressure-Controlled Excavation Technology works (Section 3), a discussion of the technology and equipment (Section 4), research methods and activities undertaken as part of this program (Section 5), and the research conclusions resulting from of this effort (Section 6).

U.S. Patent No. 6,432,303 B1, Contaminated Sediment Excavator For Subsurface Sediment Removal, and U.S. Patent No.6,712,972 B2, Enclosed Excavator for Low Moisture Contaminated Sediment Removal.

SECTION 2

CURRENT CONTAMINATED SEDIMENT DREDGING AND CONTAINMENT TECHNOLOGY

Current dredging methods can be divided into two general categories. They include mechanical dredging and hydraulic or vacuum dredging. The fundamental difference between these categories is the equipment used and ultimately the form in which the sediments are removed.

Mechanical dredging operations make use of clamshell buckets to remove the sediments. Clamshell buckets, shown in Figure 2-1, are lowered to the bottom of waterways where they scoop the sediments, capturing and bringing to the surface the bottom sediments as well as the water entrapped within the bucket. Mechanical (i.e., clamshell-bucket) dredging results in the collection of sediment with a relatively low liquid to solid ratio (i.e., relatively little water is entrained in the sediments) compared to hydraulic dredging operations. Some clamshell buckets have openings that drain the free water entrapped within the bucket to reduce the water collected with the sediment.[2]

Figure 2-1. Clamshell Buckets

Hydraulic or vacuum type dredges agitate the bottom channel to dislodge the sediment, and pump (vacuum) the sediment from the waterway. This agitation is accomplished with augers or cutterheads shown in Figure 2-2. In hydraulic dredging operations the sediment is transported in a slurry with water acting as the transport medium (see floating pipeline in Figure 2-2). This results in a water-sediment mix with a high liquid to solid ratio. The sediment in the slurry must later be segregated from the water carrier. This is typically accomplished using large impoundment areas where the sediment is extracted by settling and the water (effluent) is returned to the originating waterway.

[2] This is a highly questionable practice when contaminated sediments are being dredged since contaminated drainage is released back into the waterway untreated.

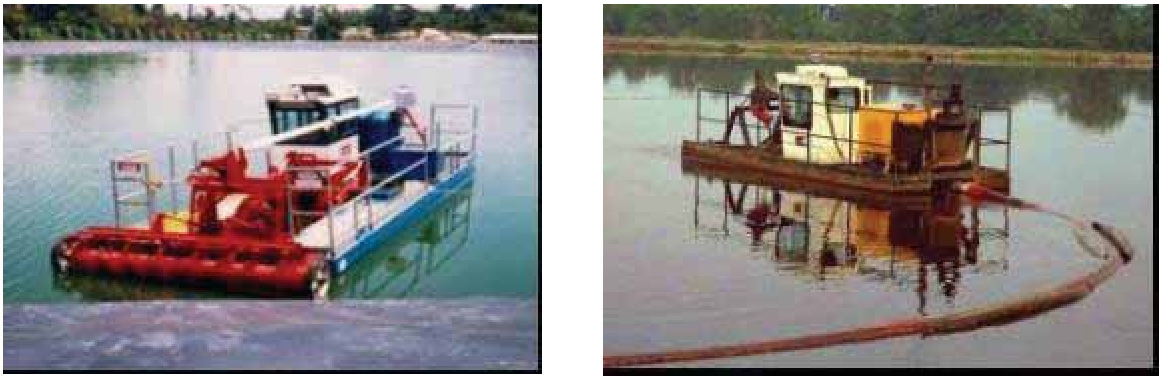

Figure 2-2. Hydraulic Cutterheads and Horizontal Augers

The problem with both mechanical and hydraulic dredging operations is that by nature they must penetrate, displace, and rake the bottom sediment in order to extract the sediment from the waterway. As noted in Section 1, such operations destroy the stability of the sediment structure at the sediment-water interface. These destabilized sediments, subsequent to the dredging operation, become more susceptible to dispersion and migration than the original pre-dredged sediments. In mechanical dredging operations, sediment dispersal is further induced when buckets are intentionally drained to reduce the water content of the collected sediments, when leakage occurs due to inadequate bucket sealing mechanisms, or when debris gets caught in the buckets, as shown in Figure 2-3. These latter issues are particular problems in debris fields where the presence of wood debris, metal debris, or large boulders will interfere with bucket operations.

Figure 2-3. Leaky Clamshell Buckets

Hydraulic dredging operations offer the advantage of a vacuum system that can assist in capturing some resuspended solids during bottom scouring operations. Nonetheless, based on the experience of the authors, the energy imparted to a large fraction of sediment particles by hydraulic dredging cutterheads that is intended to break up the cohesive forces that bond the soil so that the sediment can be sucked into the vacuum head, coupled with energy of the prevailing current(s) can be expected, to exceed the vacuum energy available to capture these dispersed particles. Hydraulic dredging operations are limited, due to vacuum head clogging problems, to areas in which the sediments have low levels of debris. Since hydraulic dredging operations generate large volumes of water, which carry the sediments, the sediments must be withdrawn from the water and the carrier-water treated prior to discharge. As a result, hydraulic dredging operations are further limited to areas where large impoundment areas exist or can be made available to collect and hold the water for treatment.

Sediment destabilization during contaminated sediment dredging operations is a special concern since the most destabilized sediments can be expected to be the fine, light, organic-rich particles. These are the sediment particles that will typically carry the highest levels of contaminant concentrations.

Physical barriers have been employed during environmental dredging operations to isolate the area of dredging and contain contaminated particulates that are dispersed into the water column during the excavation process. Two of the more common approaches include silt curtains and fixed steel sheet piles.

Silt curtains, shown in Figure 2-4, are flexible, canvas sheets that are deployed by attaching heavy ballast materials to the bottom of the fabric and buoyant floats to the top to hold the curtain in a vertical configuration. Silt curtains, however, can only be used in quiescent waterways. Locations with high currents (in excess of 0.5 knots) can disrupt and force silt curtain movement, similar to the manner in which

Figure 2-4. Silt Curtains

a wind blows a sail, causing the silt curtain to dislocate and migrate in the direction of the current.

Fixed steel sheet piles, shown in Figure 2-5, provide an alternative to silt curtains. If designed properly they can withstand significantly higher currents than silt curtains. Fixed sheet pile barriers require the installation of fixed posts and soldier beams in the waterway to support the structure. Sheets must be properly imbedded into the subsurface (vibrated or driven into the sediment) to ensure the sheet pile structure will withstand the hydraulic forces to which it will be exposed (e.g., waves and currents). A fixed sheet pile containment barrier is an immobile barrier, which in most cases will surround all equipment inside the containment area for the duration of the project.

Figure 2-5. Fixed Sheet Piles

The most notable deficiency associated with both silt curtain and fixed sheet pile containment systems is that the containment is "temporary." Once the bottom sediments are destabilized, the sediment particles are mobile and can readily migrate downstream after the silt curtains and/or fixed sheet piles are removed. This raises a serious question as to the overall effectiveness of such systems in preventing contaminated sediment migration.

Section 3

PRESSURE-CONTROLLED EXCAVATION: THE CONCEPT AND OBJECTIVES

Pressure controlled excavation employs a concept that is similar to that of a simple diving bell. A simple diving bell is a watertight chamber, opened at the bottom that is lowered into the water by cables from a crane. The chamber permits workers, located within the chamber, to perform salvage and underwater operations. The chamber is ballasted to remain upright and negatively buoyant so that it sinks when filled with air. Hoses fed by pumps at the surface provide compressed air, which serves two functions. First, the compressed gas (fresh) provides oxygen for breathing purposes and, second, the compressed air prevents water from entering the chamber as it is lowered. This simple concept is illustrated in Figure 3-1, which depicts an open bottom chamber that is lowered 10 feet below the water surface.

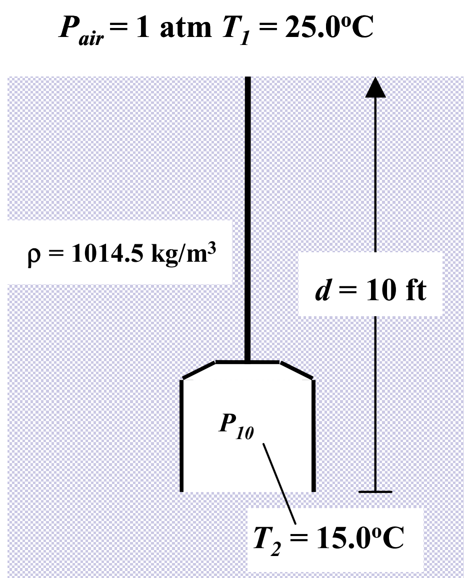

Figure 3-1: Diving Bell Concept

From a quantitative perspective, the hydrostatic (gauge) pressure exerted on the chamber is equal to the unit weight of water multiplied by the depth of water. Using the example shown in Figure 3-1, the hydrostatic pressure at a depth of 10 feet can be calculated as follows:

$$P_{10} = \gamma d$$

where,

γ = specific or unit weight of water

d = water depth

The example in Figure 3-1 depicts a brackish water system (e.g., a salinity of 20 parts per trillion (ppt) and a water temperature of 15ºC). The specific gravity of the brackish water is 1.0145. Expressed in English units, the pressure at a depth of 10 ft can be calculated as follows:

$$P_{10} = 62.4 \text{ lb/ft}^3 \text{ x } 1.0145 \text{ x } 10 \text{ ft} = 633 \text{ lb/ft}^2 = 4.40 \text{ psi}$$

To maintain an evacuated chamber, the air pressure inside the chamber must be capable of withstanding the external hydrostatic pressure of 4.40 psi. Given the volume of the chamber, the quantity (mass) of air that must be introduced into the chamber or released from the chamber and the corresponding increase or decrease of the applied air pressure within the chamber can readily be determined.

While the primary function of the diving bell is the balancing of compressed air and hydrostatic pressure to maintain adequate working space and breathable air space for workers in a subaqueous environment, the primary function of Pressure-Controlled Excavation technology is the balancing of air pressure inside the chamber and hydrostatic pressure to introduce new control into the dredging process.

Employing Pressure-Controlled Excavation in a dredging application requires the use of a chamber or enclosure that houses an excavation device (i.e., bucket) inside and contains an open (or partially opened) bottom. Similar to a diving bell, the air pressure inside the watertight enclosure can be controlled to prevent water from entering the enclosure. Reducing enclosure pressure, below the hydrostatic pressure at a given depth, allows water to flow from outside the enclosure into the enclosure. If a sufficient difference in air pressure and hydrostatic pressure is achieved, water drawn into the enclosure can carry loose sediment particles that would normally be dispersed during the dredging process. This water-sediment slurry can subsequently be pumped to the surface for treatment as the enclosure is lifted upward through the water column.

In summary, the primary objectives of Pressure-Controlled Excavation are to mitigate problems with contaminated sediment migration from the dredge site and to remove destabilized contaminated sediment particles that may be left behind during the dredging process. This can be achieved by alternate cycles of positive and negative pressure within the enclosure to control water intake and collect sediment particles during the dredging process. As part of the process, dispersed sediment particles collected during the dredging are pumped to a water treatment facility to remove the collected particles so that the pumped water can be safely returned to the waterway.

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Section 4

PRESSURE-CONTROLLED EXCAVATION: THE TECHNOLOGY

The translation of a pressure-controlled excavation concept to a working technology required the development, design, construction, and testing of a physical system capable of performing in accordance with the intended specifications. Section 4 presents a description of the key design issues and the primary electromechanical and hydraulic equipment that comprised the physical system.

The primary component of the system is a specially designed enclosure or housing that envelops a mechanical dredge (clamshell bucket). Within this enclosure the alternating cycle of positive and negative pressure can be introduced.

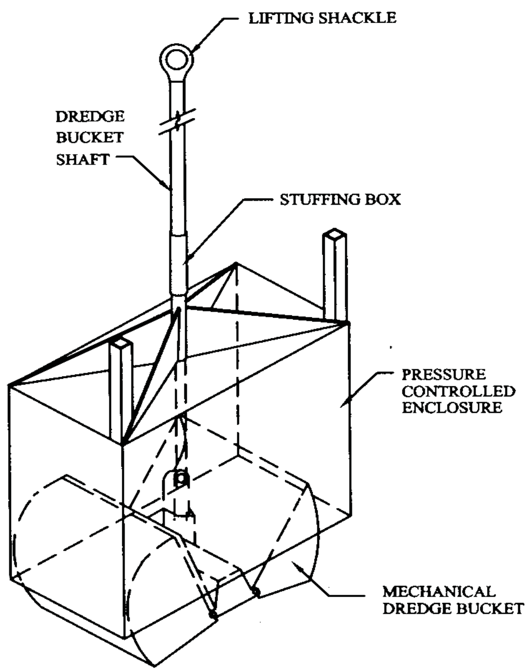

Figure 4-1: Enclosure and Bucket

An isometric view of the pressure-controlled enclosure housing a mechanical dredge (i.e., clamshell bucket) is shown in Figures 4-1, 4-2, and 4-3. The design shown in Figure 4-1 includes a lifting shackle connected to a dredge bucket shaft which, when connected to a crane or preferably a front-end loader, can be used to lower both the enclosure and mechanical bucket contained within the enclosure. The dredge bucket shaft is connected to the top of the enclosure with a stuffing box to prevent leakage into the shaft or loss of pressure inside the enclosure.

One of the critical issues associated with the design of the enclosure centered around the need for a bottom door, which could be opened to permit the bucket to be lowered into the sediment during the excavation process and closed as the housing and bucket are raised to the surface to prevent sediment from leaking and draining back into the water column. A normal rectangular door, hinged either on one or both sides of the bottom of the housing (similar to cellar doors), would open downward. Such a swinging door would interfere with the descent of the enclosure to the bottom of the waterway and would not be practical. To resolve this problem, the enclosure design concept incorporated the use of a uniquely designed rotating single-hinged door. This rotating door is shown in Figure 4-2 in both the fully opened and fully closed positions. This door can be deployed in an open position during the submersion cycle of the operation, and in a closed position following the excavation process or recovery cycle. Since it rotates upward, away from the bottom of the housing, it would not interfere with the descent of the enclosure. It would remain closed as the enclosure is lifted from the sediment and reopened when the sediment load is discharged to a top surface dredge barge or other container designed to collect and dispose of the dredge material. The single-hinged door can be opened and closed with a door control piston, which is attached to piston support columns.

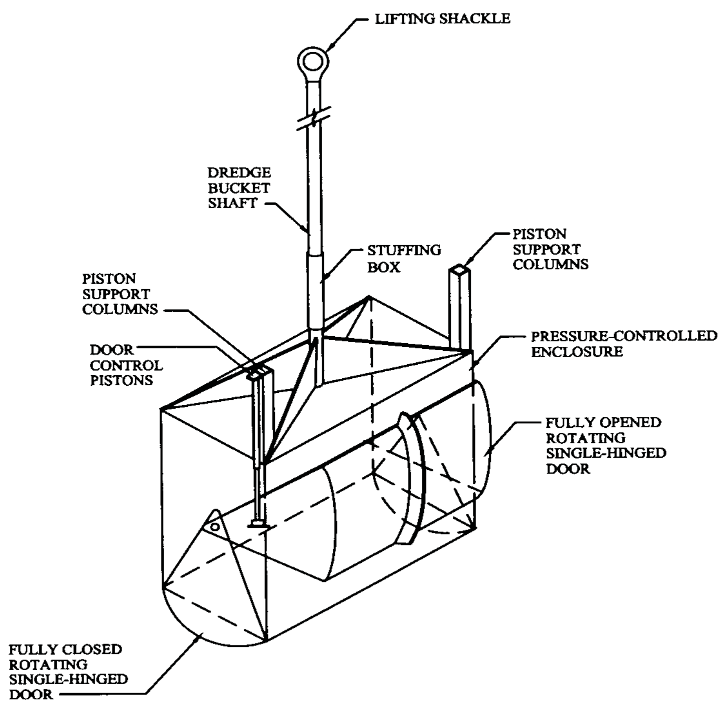

Figure 4-2: Enclosure with Single Hinged Door

While pressure control inside the enclosure can draw water with dispersed sediment particles into the housing, the collected slurry needs evacuation before the enclosure reaches the surface. As long as the enclosure is below the water surface, the collected slurry would be contained by the external hydrostatic pressure inside the housing. However, when the enclosure is lifted above the air-water surface, the external hydrostatic pressure would be lost, and unless the enclosure was sealed, the slurry would no longer be contained inside the enclosure. As a result, the design incorporated a water pump line (flexible hose) and a submersible pump as shown in Figure 4-3, outfitted to the rotating single-hinged door to evacuate the water drawn into the pressure-controlled enclosure during the recovery cycle of the operation.

A pneumatic pressure line was incorporated into the design to introduce compressed air pressure into the enclosure and release over-pressurized air from the enclosure. Access was also provided for the hydraulic bucket control line. This line is used to open and close the mechanical dredge bucket. A hydraulic door control line was also included to drive the door control pistons. The hydraulic line used to drive the pump and the interior (inside the enclosure) hydraulic line for the mechanical dredge are not shown on the drawings, but were included as part of the system design.

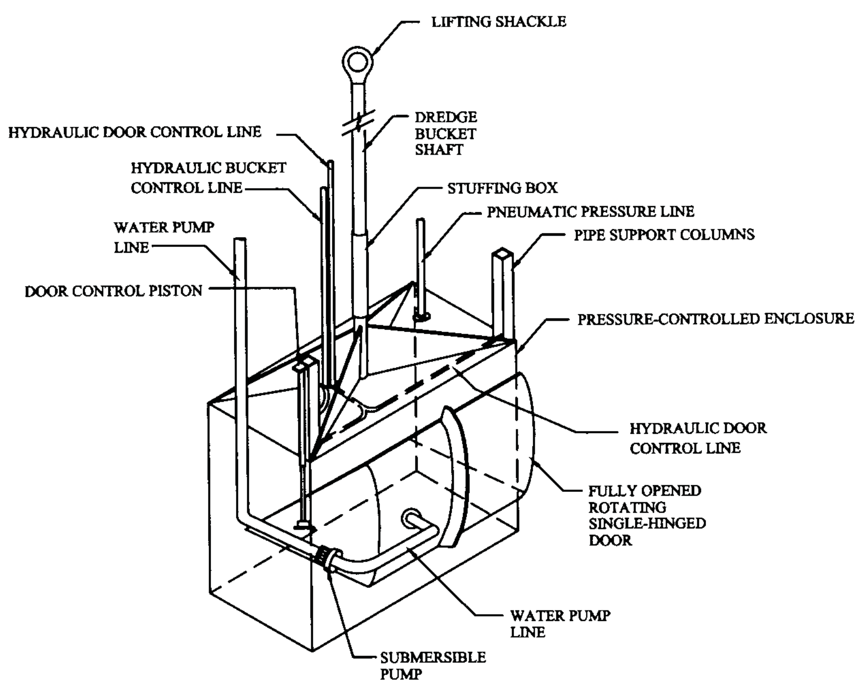

Figure 4-3: Enclosure Utilities

To provide for pressure control, the enclosure design required the development of a pressure control system that could monitor and control the internal enclosure operating pressure. The design incorporated a system of pressure transmitters, pressure regulators, and a pressure controller to monitor the internal (enclosure) air pressure, the external hydrostatic pressure and to provide a digitized feedback control system capable of constantly adjusting pressure to meet system needs. A simplified schematic of the feedback control system design is illustrated ion Figure 4-4.

The heart of the pressure control system is the controller. The controller monitors the hydrostatic pressure (external transducer), the air pressure inside the enclosure (internal transducer) and provides feedback to the pressure regulators PR-1, PR-2, and PR-3. The pressure regulators open and close in response to data transmitted from the controller. The PR-1 and PR-2 regulators, shown in Figure 4-4, represent two enclosure venting regulators.[3] These regulators are designed to release the pressure in the enclosure. The PR-3 regulator is the air compressor regulator and is designed to increase pressure inside the enclosure by the air controlling compressor input.

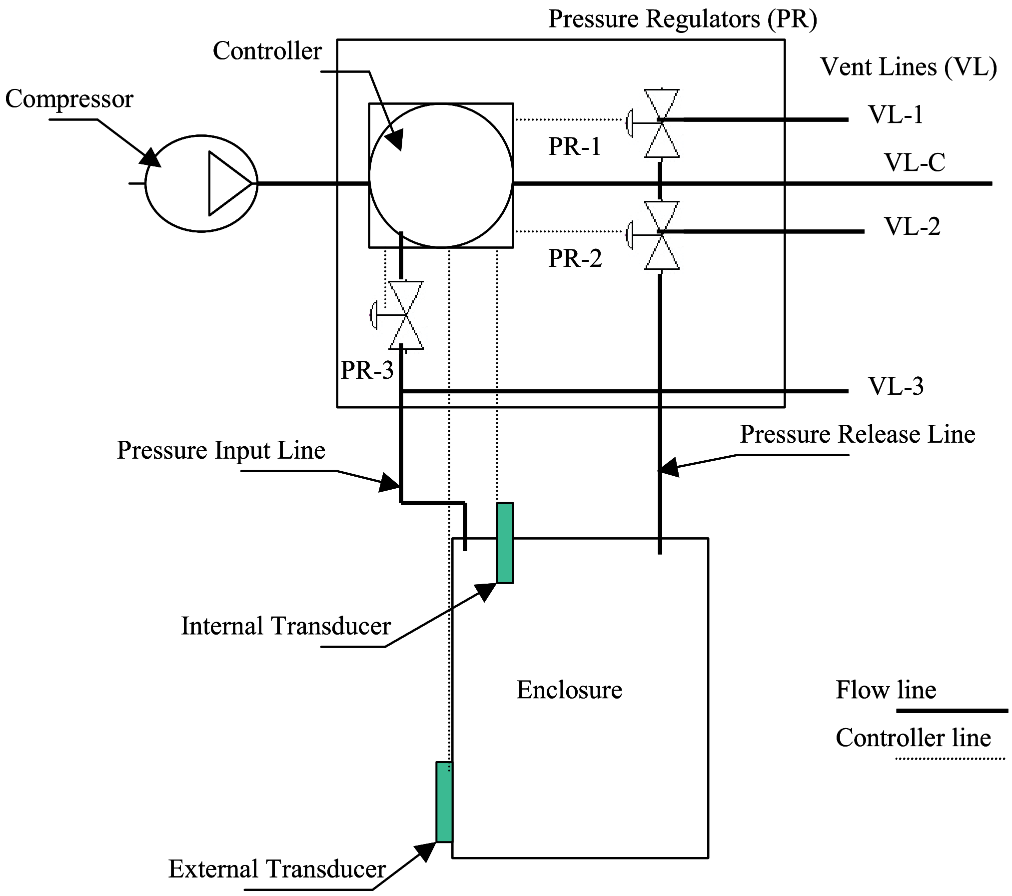

Figure 4-4: Pressure Controller Feedback Control System

[3] Two venting regulators were incorporated as a result of research activities described in Section 5.

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Section 5

RESEARCH METHODS AND ACTIVITIES

Development of the subject technology proceeded in a series of five stages culminating in the development and testing of a field prototype unit, which marks the present status of the technology. The developmental stages included:

Concept Development

Small Scale Prototype

Field Prototype Development

Control System Development, and

Tank and Field Testing.

Although each of the stages is listed independently and sequentially, the actual progress of the research effort, as it was conducted, required redirection and feedback between the individual stages. This resulted in numerous reevaluations and redesigns as the development process proceeded. A description of the progress and results of each developmental stage is presented below.

1. Concept Development

The concept development stage included the formulation of the initial concept design strategy outlined in Section 3. The driving force behind the concept was the recognition that existing mechanical dredging technology (i.e., the use of clamshell buckets for dredging) provides little if any positive control to contain and capture dispersed sediment generated during a contaminated sediment removal operation. The operation, due to its nature, destabilizes and disperses the contaminated sediments and the only question is the degree of dispersion and subsequent impacts. Control is limited to containment strategies, discussed in Section 2, and these strategies do not provide any real positive control.[4]

Development of the Pressure-Controlled Excavation concept was envisioned as a means to incorporate the benefits of incorporating a low-pressure zone at the location of the dredge to capture destabilized sediments that would otherwise be lost in the dredging process. Capturing these destabilized particles could prevent their migration to other locations and reduce the level of residual contamination left behind after dredging

[4] Note that positive control is defined here as a control that mitigates problems of sediment destabilization (by removing the sediment from the waterway) and not simply contain it temporarily which is the function of conventional containment strategies outlined in Section 2.

is completed. In addition it was also envisioned that the excavation of sediment in a water-free environment could potentially reduce the moisture content of the excavated sediment, thereby reducing subsequent sediment handling and disposal costs.

The basic concept envisioned a system in which a clamshell bucket, deployed inside a pressure-controlled enclosure, would be lowered to the bottom of a waterway at an internal pressure that prevents water from entering the enclosure. During the excavation process, pressure in the chamber would be reduced, drawing water into the chamber along with particles that would normally be dispersed during the dredging process. The water-sediment slurry would subsequently be pumped to the surface for treatment during the ascent of the chamber through the water column. This pump-and-treat step necessitated the design of a complimentary mobile water treatment platform that would be integrated into the dredging operation. The water treatment concept developed included a system that could remove particulates through the addition of flocculants in a settling system, followed by more rigorous treatment if needed. This more rigorous treatment envisioned the use of a membrane filtration system for very fine particulate removal (e.g., less than 0.1 micron) and activated carbon treatment for soluble organic removal, if needed.

2. Small Scale Prototype Development

The practical application of a pressure-controlled excavator necessitated the development of an enclosure that would maintain the appropriate air pressure to balance the external hydrostatic pressure and house a mechanical bucket, used to excavate the targeted sediment. It would need an opening at the bottom to permit the bucket to both scoop in the sediments and draw in dispersed sediments from a local zone of influence induced by low pressure within the enclosure. In addition, to avoid the release of sediments or liquids back into the water column after the excavation, a bottom enclosure door would be needed.[5]

As part of the developmental process, a small laboratory scale enclosure was designed and constructed to evaluate both the configuration of the enclosure and the type of enclosure door that could be employed on the developing system. As part of the design, the rotating single-hinged door, previously discussed in Section 4, was developed and incorporated into the design plan (see Figures 4-1, 4-2, and 4-3). Photographs of this small prototype enclosure and the single hinged rotating door are shown in Figures 5-1 through 5-4.

Figures 5-1 and 5-2 show the deployment of a small sampling dredge inside the prototype enclosure with the single-hinged rotating door in an open position. In Figure 5-2 the bucket is in an open position, which depicts its position prior to extraction of a bucket of sediment. Figures 5-3 and 5-4 show a better view of the single hinged door powered by an air piston. In Figure 5-3 the door is in the open position and in

[5] Requirements for a door would be most critical when the housing breaks the air-water surface and all pressure in the enclosure would be reduced.

Figure 5-4 the door is in the closed position. The small-scale model was used to verify the feasibility of the initial concept and the workability of the rotating door.

3. Field Prototype Development

After the initial design layout and preliminary features of the small prototype were established, development of a field prototype followed. This stage involved upscaling the small prototype to a size that could be used in subsequent tank and field testing.

Figure 5-1: Extractor Inside

Figure 5-2: Opened Extractor Inside

Figure 5-3: Enclosure Door & Hydraulic Control

Figure 5-4: Sealed Excavator

To upscale the small-scale enclosure model to a field-size unit, a dimensional evaluation was undertaken. This involved the selection of some key dimensional design parameters. The initial design parameter that was defined was the relative outlet volume ratio. This parameter represents the ratio of the design bucket volume (V_B) and design enclosure volume (V_E). The relative bucket volume ratio (V_B/V_E) is a design parameter that establishes the relative space in the enclosure occupied by the bucket. Another selected design parameter, the volumetric water capacity (V_W) was determined. This parameter represents the difference between the enclosure volume (V_E) and the bucket volume (V_B), when the bucket is full of sediment during the excavation process.

This design parameter establishes the volume of water that could be drawn into the enclosure during the excavation process and the potential zone of influence or volumetric area that could be collected for treatment during the excavation. Mathematically the volumetric water capacity of the enclosure (V_W) is defined as follows:

$$V_W = V_E - V_B.$$

Additional discussion concerning the volumetric water capacity and the zone of influence is presented below.

An analysis of the enclosure buoyancy was necessary to ensure that the enclosure would submerge (i.e., negative buoyancy). The buoyancy is directly related to the value of V_E and required that the weight of the enclosure W_E be greater than the weight of water inside the enclosure. Expressed mathematically,

$$W_E > \gamma V_E$$

where γ is the unit weight of water.

Finally, the volume (V_E) and dimensions of the bucket were used in determining the overall size of the enclosure and relationship between the enclosure height (h_E), breadth (b_E) and depth (d_E).

A one-half cubic yard bucket was selected as a suitable size for the field prototype system. A photograph of the one-half cubic yard bucket used in the design and fabrication of the field prototype is shown in Figure 5-5. The one-half cubic yard bucket dictated the values of b_E, d_E, and h_E, which were sized in a ratio of 5, 2.5, 4, respectively, which corresponded to dimensions of b_E = 60 in., d_E = 30 in., and h_E = 48 in. Figure 5-6 illustrates the specific configuration of the enclosure and the dimensions b_E, d_E, and h_E.

Figure 5-5: One-Half Cubic Yard Bucket

A series of photographs presented in Figures 5-7, 5-8, 5-9 and 5-10 show selected views of the unpainted field prototype unit with the rotating door fully opened, in a partially opened and fully closed position, respectively. Figure 5-10 shows the one-half cubic yard bucket housed inside the enclosure.

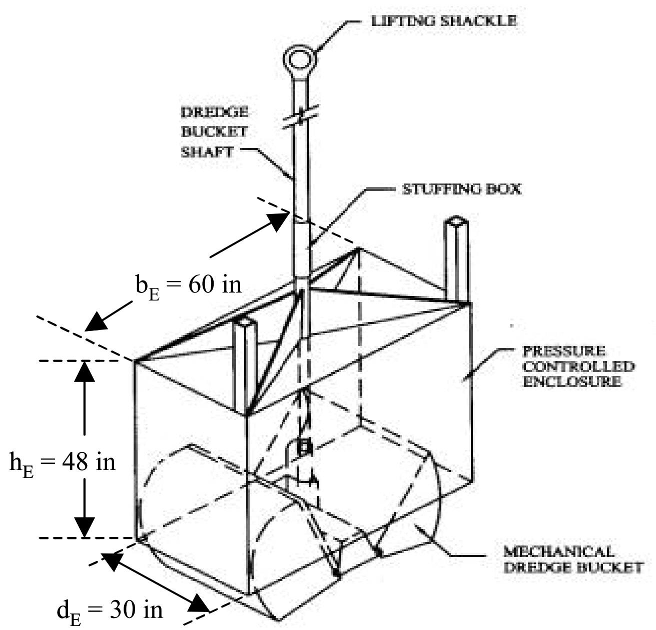

Figure 5-6: Enclosure Dimensions

The dimensional design of the field prototype enclosure is presented in Table 5-1. The enclosure design provides for a total volume (V_E) of approximately 1.85 yd^3 and a bucket volume (V_B) of 0.5 yd^3, resulting in a V_B/V_E ratio of approximately 0.27. This design provides a volumetric water capacity (V_W) of approximately 0.73 V_E, or 1.35 yd^3.

Figure 5-7: Enclosed Excavator with Open Door

Figure 5-8: Enclosed Excavator with Partially Closed Door

Figure 5-9: Enclosed Excavator with Fully Closed Door

Figure 5-10: Enclosed Excavator Maintenance Hatch

Table 5-1
Field Prototype Enclosure
(Dimensional Design)

Breadth (b_E)	=	5 ft
Depth (d_E)	=	2.5 ft
Height (h_E)	=	4 ft
Volume (V_E)	=	50 ft^3 = 1.85 yd^3
Volume (V_B)	=	13.5 ft^3 = 0.5 yd^3
Water Volume Capacity (V_W)	=	$V_E - V_B$ = 1.35 yd^3
Relative Bucket Volume Ratio (V_B/V_E)	=	0.27

The volumetric water capacity (V_W) is a design parameter that provides information relative to the pumping rate that is needed to evacuate the enclosure and to maintain a negative pressure inside the enclosure during enclosure ascent from the waterway bottom.

It also provides a measure of the initial zone of influence around the enclosure bottom that will be affected by the directed drop in air pressure inside the housing during the excavation process. A V_W value of 1.35 yd^3 for the field prototype indirectly translates into an equivalent volumetric zone of influence.

During operations, when the excavator is lowered with a crane to the sediment-water interface, the enclosure settles under its own weight into the sediment. Alternately, when the excavator is deployed with a hydraulic excavator the enclosure is pushed into the sediment surface. After the enclosure is set into the sediment, the clamshell bucket, inside the enclosure, is lowered to the sediment-water interface and begins its cut into the sediment. After biting into the sediment, the bucket closes and is subsequently pulled up into the enclosure. As the bucket is drawn upward into the enclosure, the enclosure begins its slow ascent. As the ascent begins, the pressure inside the enclosure, relative to the external hydrostatic pressure, is reduced. When the bottom of the enclosure breaks the sediment-water interface, the lower pressure inside the enclosure induces the inward flow of water.

Theoretically, if one assumes that all water drawn into the enclosure comes from below the enclosure bottom when the internal enclosure pressure is reduced, the three dimensional coordinates of the zone of influence can be approximated by calculating the radius (r_I) comprising a circle whose center is located at the midpoint of the enclosure, when viewed in a horizontal plane, and when the enclosure is located a prescribed distance (d_I) above the sediment-water interface. Mathematically r_I can be expressed as follows:

$$V_W = \pi (r^2_I)(d_I), \text{ and}$$

$$r_I = (V_W/\pi\, d_I)^{1/2}$$

As an example, the zone of influence, can be defined by r_I, for the field prototype, when the enclosure is located one ft above the sediment water interface (i.e., $d_I = 1$) as follows:

$$r_I = (36.5/\pi)^{1/2} = 3.4 \text{ ft.}$$

This means that the zone of influence will extend 3.4 feet from the center of the enclosure as shown in Figure 5-11.

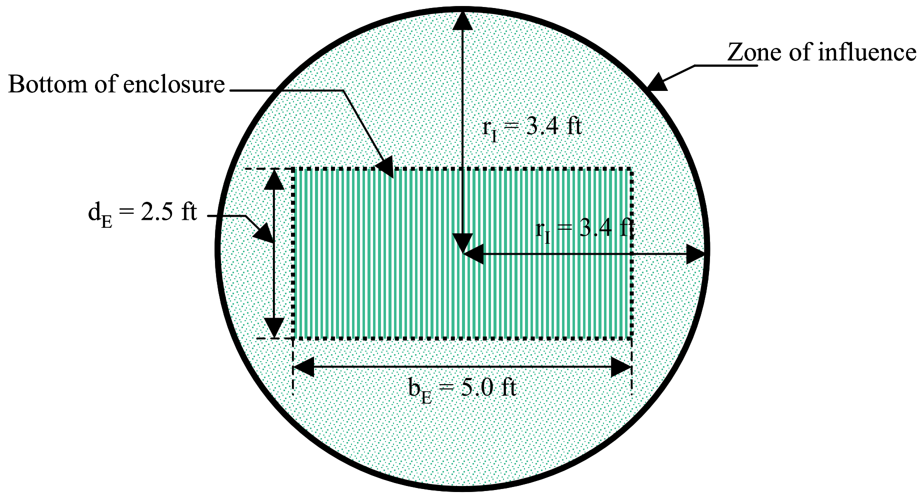

Figure 5-11: Approximated Low Pressure Zone of Influence at d_I= 1 ft

The analysis as presented assumes that all external water entering into the enclosure will be drawn from the head space below the enclosure (i.e., space between the enclosure and the sediment bottom). This is not accurate. Water will be drawn in around the edges of the enclosure (from above the enclosure head space), however frictional resistance to flow in this zone will reduce the overall quantity. Nonetheless to more accurately depict the zone of influence a reduction factor (k_R) for the radius of the zone of influence is needed. Mathematically, the equation for r_I can be adjusted as follows:

$$r_I = k_R \, (V_W/\pi d_I)^{1/2}$$

Assuming k_R = 0.85 (subject to further research), the revised value of r_I is 2.9 ft. This value suggests that all areas below the enclosure would be included in the zone of influence.

4. Control System

The final control system concept, presented in Figure 4-4, was the result of iterative trials during tank testing and field testing. The results of this testing and evaluation program are summarized in subsection 6, which presents the results and discussion of the control system evaluation.

A programmable controller (ER3000), manufactured by the TESCOM Corporation, was selected as part of the design to provide the tracking of internal enclosure air pressure and external hydrostatic pressure, and to provide control over the valves (open and close) of the three pressure regulators (i.e., PR-1, PR-2, and PR-3 shown in Figure 4-1). The pressure transducer signals sent to the ER3000 were deduced to determine whether more or less pressure would be needed in the enclosure at a particular moment. Pressure transducers located inside and outside the enclosure were used to record enclosure air pressure and external hydrostatic pressure, respectively.

As an example, during descent when the hydrostatic pressure is increasing, the PR-3 regulator (see Figure 4-1) would normally be directed by the controller to open to permit compressed air to enter the chamber to balance the internal enclosure air pressure with the increasing hydrostatic pressure. During enclosure ascent when the hydrostatic pressure is being reduced, the venting pressure regulators (i.e., PR-1 and PR-2) would normally open to vent excess air, maintaining the internal-external pressure equilibrium.

During tank and field testing it was determined that a double venting regulator system (i.e., PR-1 and PR-2) was needed to provide coarse and fine control during the excavation operation. It was found that fine venting control was the preferred mode of operation during periods of slow enclosure ascent. However, during periods of more rapid ascent or during the period when a bucket full of sediment is drawn into the enclosure, more rapid venting is required to avoid over-pressurizing the enclosure.

A series of photographs are presented in Figures 5-12, 5-13, 5-14, and 5-15, which illustrate the major components of the control system.

Figure 5-12 is a photograph of the master control center showing a view of the controller, regulators, and gauges. A close-up view of the pressure gauges is shown in Figure 5-13. The gauges provided visual information of the enclosure air pressure, the hydrostatic pressure and the difference between the two. (Note: the goal being to have the difference equal to zero). Figure 5-14 provides a close-up view of the ER-3000 controller. This controller is wired to a computer (not shown), which contains the software needed to program the controller. The controller is in turn connected to each regulator providing the necessary control to direct the system. A close-up view of the controller and pressure regulators are provided in Figure 5-15.

Figure 5-12: Master Control Center

Figure 5-13: Visual Gauges at Control Center

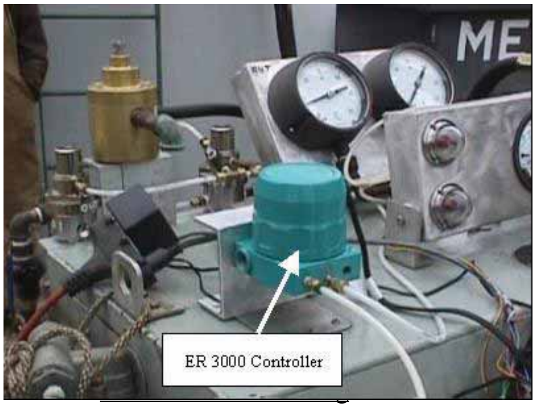

Figure 5-14: ER-3000 Controller

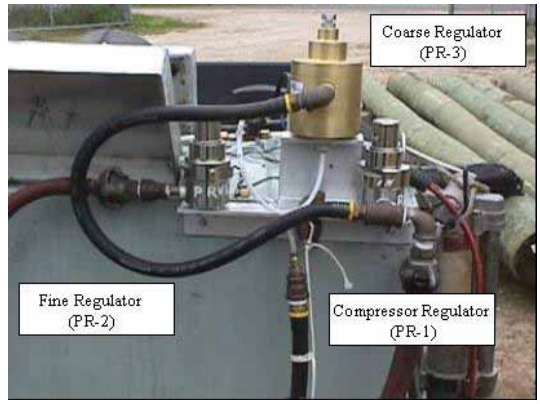

Figure 5-15: Pressure Regulators

The final stage of the research and development effort included a series of tank and field tests to assess the performance of the system under field conditions. As noted previously, the research and development process did not proceed in a smooth sequential pattern as defined by the five stages described in the text. The tank and field testing stage in particular had a profound effect on the final system design. The results of tank and field tests provided constant feedback to the field prototype and control system design that resulted in the final system.

Photographs of the final pressure-controlled excavator that was used in the tank and field tests are shown in Figures 5-16 and 5-17.

Figure 5-16: Pressure Controlled Excavator: Compressed Air Hosing and Rotating Door

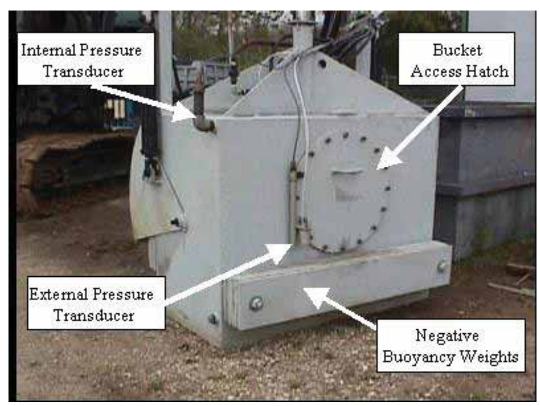

Figure 5-17: Pressure Controlled Excavator: Negative Buoyancy Weights, Access Bucket Hatch, Pressure Transducers

Tank testing was undertaken at the Seaway Environmental Technology test site in Greenport, NY. Two types of tanks were used in the test program: 1) a 4 ft high tank and 2) a 12 ft high tank. During tank testing the excavator was submerged in each tank to evaluate the efficacy of the control system with respect to its suitability to monitor and control internal enclosure pressure with depth. Photographs of the excavator being submerged in 4 ft and 12 ft tanks are shown in Figures 18 and 19, respectively.

To evaluate the control system, tracking of internal (enclosure air pressure) and external (hydrostatic pressure) transducer readings in the excavator were monitored. The results of one of a series of such tracking tests in the 12 ft tank are presented in graphical format in Figures 5-20 and 5-21. Figure 5-20 provides a graph of continuous readings during one submergence (i.e., descending) 12 ft tank test and Figure 21 provides continuous pressure readings during emergence (i.e., ascending) 12 ft tank test. The "setpoint" notation in each figure represents the external transducer reading (hydrostatic pressure) and the "feedback" notation represents the internal transducer reading (enclosure air pressure).

Figure 5-20 provides continuous readings from an arbitrary time equal to zero seconds, at which the setpoint read approximately 1.2 psig, to 400 seconds at which time the reading was approximately 3.6 psig. A value of 1.2 psig corresponds to a submerged depth of approximately 2.8 ft and a value of 3.6 psig corresponds to a submerged depth of 8.3 ft.[6]

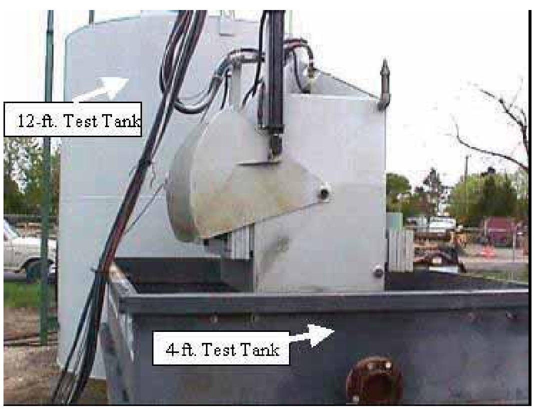

Figure 5-18: Pressure-Controlled Excavator: 4-Foot Tank Test

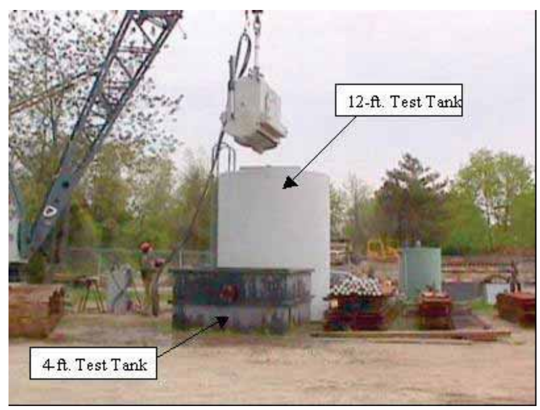

Figure 5-19: Pressure-Controlled Excavator 12-Foot Tank Test

The graphed data show the pressure effects associated with the submergence of the enclosure from the initial depth of 2.8 ft (reflected by the 1.2 psig reading), to a depth of approximately 6 ft after 50 seconds (reflected by the 2.6 psig reading, to the final depth of 8.3 ft (reflected by the 3.6 psig reading). Note that the enclosure was held for approximately 250 seconds at the 6 ft depth before descending to the final 8.3 ft depth.

[6] The submerged depth represents the depth of water measured from the top surface to the bottom of the housing. Gage pressure readings contained a correction factor to account for the fact that the external pressure transducer (see Figure 5-17) was offset 18 inches from the bottom of the housing. The submerged depth in feet was calculated by multiplying the gage pressure (psig) by 2.3.

The graphed data in Figure 5-21 show the pressure effects associated with the emergence of the enclosure from a depth of 8.3 ft until the enclosure broke the water surface of the tank. The data illustrates a tight tracking of the setpoint and feedback. The break between the setpoint and feedback in Figure 5-21 reflects the fact that the enclosure broke the water surface, which disrupted the transducer measurements.

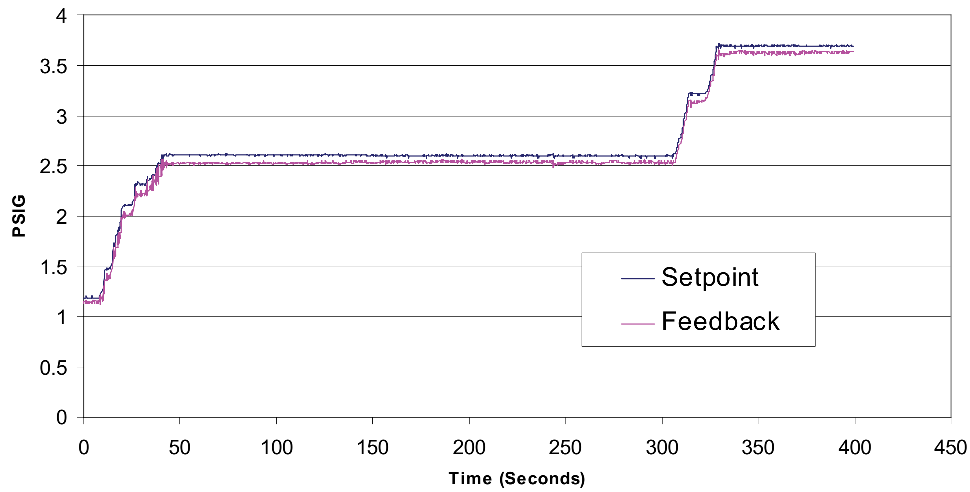

Figure 5-20: Pressure-Controlled Excavator 12-ft Tank Test: Descending Readings

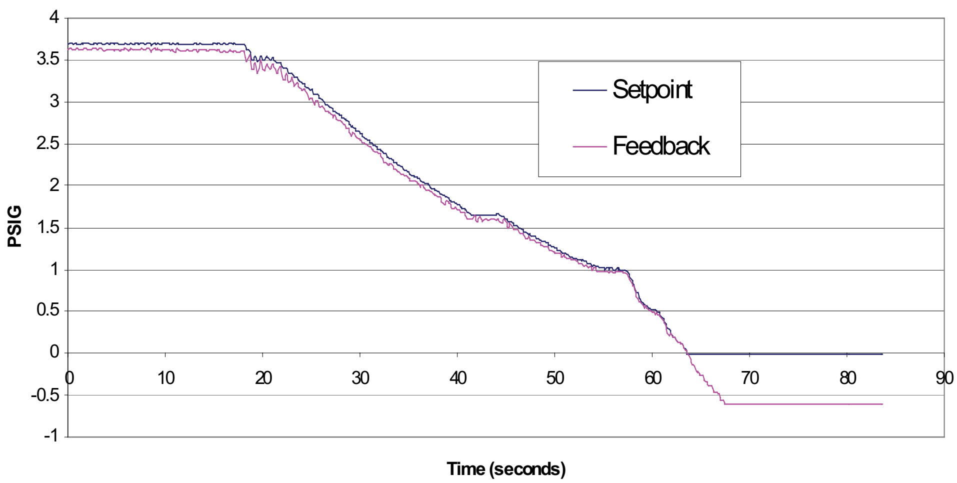

Figure 5-21: Pressure-Controlled Excavator 12-ft Tank Test: Ascending Readings

After the successful completion of the control system tank testing program, the research effort shifted to field testing. Field testing was performed during the fall of 2003 and the summer of 2004 at a permitted test facility at Cedar Beach in the Town of Southhold, Long Island. Testing was undertaken in a tidal zone with water elevations ranging from 6 ft to approximately 12 ft.

Field testing that was undertaken was similar to tank testing, except that during field testing the excavation component (i.e., excavation of subaqueous sediments) was included as part of the test evaluation. Photographs of the field testing site and the actual testing activities are shown in Figures 5-22 through 5-27.

Figure 5-22 shows the field prototype enclosure at the field testing site with the bucket maintenance hatch open. Figure 5-23 shows the enclosure being lifted prior to descent into the water column. Figure 5-24 shows a closer view of the prototype field unit prior to excavation and Figure 5-25 shows the unit entering the water column. Figure 5-26 shows the submerged excavator and Figure 5-27 shows an over-pressurized excavator discussed below.

Figure 5-22: Field Prototype

Figure 5-23: Crane Deployment

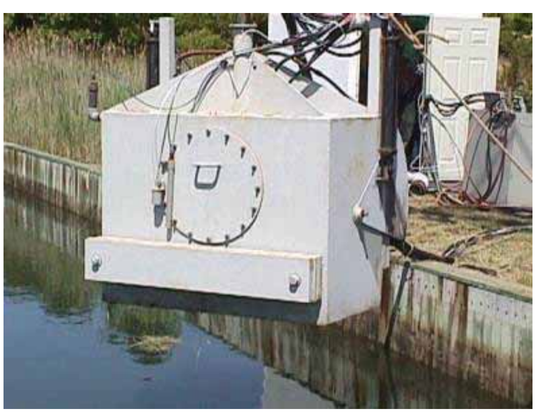

Figure 5-24: Field Prototype Unit Prior to Submergence

Figure 5-25: Field Prototype Unit Descending for Excavation

Figure 5-26: Submerged Field Prototype

Figure 5-27:Over-Pressurized Field Prototype

The field testing program was partially successful. While the excavator was capable of successfully extracting and removing sediment from the bottom surface, pressure control was not completely satisfactory.

The primary field problem was the increasing pressure induced by the sediment excavation process. Bringing sediment into the pressurized housing during the excavation process resulted in a rapid over-pressurization of the air inside the housing. The control system was unable to adequately respond to this over-pressurization. A satisfactory response would have resulted in a rapid detection of the increasing pressure induced by the excavation, coupled by a corresponding shutdown of the intake compressor air venting and through the coarse regulator of the over-pressurized air. The control system was incapable of responding rapidly enough to prevent this over-pressurization.

During the field testing program, the over-pressurized condition in the enclosure was relieved by venting through the bottom of the housing. Such a condition at an actual contaminated sediment site would be problematic because the bottom venting would disturb the bottom sediment. The Figure 5-27 photograph shows the bubbling water surface during an over-pressurization test run.

Section 6

RESEARCH CONCLUSIONS

The research effort described in this report focused on the development of a Pressure-Controlled Excavator to remove contaminated sediments from waterways in a manner that would prevent the migration of sediment from the cleanup site and reduce the level of residual contamination left behind by the dredging process.

The research effort resulted in the successful development and operation of the physical components of the system as follows:

The unit was successfully submerged and pressurized during submergence.

The rotating door was successfully opened and closed during all phases of the operation.

A balance between the internal air pressure and the external hydrostatic pressure was successfully controlled during submergence and emergence operations.

The enclosure was successfully placed over the area to be excavated and the mechanical bucket was successfully extended into the bottom surface to collect sediment.

It was determined that a hydraulic excavator would provide better control, however, than the crane used in the test program.

Difficulties, however, were encountered in adapting the control system to the full range of conditions encountered at a dredge site. It was concluded that additional effort is needed to develop more precise control of the pressure regulators used in the process to control pressure during rapid changes in pressure encountered during field operation. This effort would involve additional design and testing activities that could not be completed within the scope of the current effort.

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Pressure-Controlled Excavation Technology for Contaminated Sediment Removal

Final Report 05-06b

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