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USE OF CRYOGENIC BUOYANCY SYSTEMS FOR CONTROLLED REMOVAL OF HEAVY OBJECTS FROM THE SEABED

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ABSTRACT

New methods for marine salvage and decommissioning of structures in the open sea are continually being sought in order to improve control and lower operational costs. This paper investigates the concept design of a lightweight cryogenic marine heavy lift buoyancy system. The approach makes use of a cryogenic system for provision of buoyancy within the ocean environment. The objective is to be able to lift or lower large displacement objects under full remote control. The opening stages of the project work include the development of a system that will operate to a depth of 350m. As part of the design process for such an arrangement, numerical simulation of the complete system has been undertaken in order to develop mechanical, cryogenic and process control systems. The paper considers the overall design concept and associated system development issues. These are illustrated through use of the time accurate simulation of alternative design configurations that confirm their viability.

INTRODUCTION

Numerous methods of lifting and lowering objects from the seabed have been developed throughout the history of ocean engineering and exploration. Initially, these methods were in practice for the purpose of marine salvage. The first evidence of marine salvage in operation was in 460 B.C., where mention is made of a Greek diver being hired to remove treasure from shipwrecks [1]. Most of the early divers went free diving – using no equipment and staying submerged as long as a breath lasted, this could be as long as 5 or 6 minutes! It was not until the development of a method to supply divers with surface air that diving was really used for salvage operations. From this point on diving became not only a recognized method for salvage, but also a method for deploying and recovering sub-sea equipment.

Since then, many techniques have been used to recover objects from the depths that are much too large for a diver, or even indeed a team of divers, to handle. These include methods such as compressed air being pumped down through lines to fill vessels that had been sealed by divers, building a coffer dam around the object and pumping out the water, and pumping polyurethane foam into hollow objects to provide enough buoyancy to float them free[1]. All these methods have limitations on their scope of operation. Techniques using divers are limited to the maximum depth a diver can descend to without coming to harm, dam building can only be done in shallow water.

The methods more commonly used today include cranes and lift bags and an assortment of Remotely Operated Vehicles (ROVs). Cranes are popular for deep water lifts, and can be used to depths of 2000m, but are not without problems. The weight of the cable can end up being more than that of the payload for deeper lifts making the process awkward and costly. There is a limiting sea state due to the motion of the vessel on which the crane is mounted, which leads to operational constraints due to predicted weather windows. Ultimately, it is the excessive cost of hiring and the limited availability of the cranes which are the main problems. For the case of lift bags, control is the limiting factor. The open bottom bags dump excess air from the bottom as they ascend, and the enclosed lift bags only have a limited capacity to dump air through pressure release valves. As such the rate of ascent tends to be controlled somewhat coarsely by adding more weight to the bags, and the slow steady ascent often required for structurally unsound objects is not achieved. ROVs on the other hand are highly controllable, and have been designed to cope with the extremely high pressures at very deep depths (circa 6000m). ROVs, however, are complex systems and require power supplied by means of an umbilical for operation. As such, the mass that these vehicles can lift is limited by the size and power of the thrusters which are used for propulsion.

Ensuing from this there is a continual drive to develop new concepts for the salvage, decommissioning of offshore structures, and even launching of new structures. Such designs must be remotely operated, safe, cost effective and environmentally responsible, with high levels of control and can therefore overcome the problems associated with current launching and recovery apparatus. Even with new concepts that have been generated there are significant problems that need to be overcome. The Controlled Variable Buoyancy System (CVBS), for example, was unsuccessful due to the low lifting load of each unit which meant that many units were required for one lift, each requiring a complex arrangement of umbilicals and many air compressors for operation. The surface support vessels could also be moored no nearer than one mile away causing these umbilicals to become long and the whole system very complex [2].

This paper introduces a new concept design for a remotely controlled, deep sea, launch and recovery system. The challenges faced in the design and development of such a vessel are discussed and conclusions made as to the most appropriate cryogen required and the dependency of the mass of the system on operation depth.

THE CONCEPT

A consortium of companies led by Deep Sea Recovery Limited (DSR) has received a grant from the Technology Strategy Board (TSB) to develop a new method of lifting and lowering massive underwater objects. The objective of the project is to investigate the use of lightweight materials in the construction of a 'Lightweight Cryogenic Marine Heavy Lift Buoyancy System'. The materials selected must be capable of performing in a highly aggressive sub-sea environment, at pressures of between 0 bar to 33 bar and within a temperature range of -200ºC. to +50ºC. In addition to being able to perform repeatedly within these challenging parameters the overall weight of the entire system must have a slight negative buoyancy, thus requiring the use of specific lightweight materials.

The project is novel in several ways: primarily in its use of a complete cryogenic system within the deep ocean environment. The purpose is to lift and lower large displacement objects under full remote control. Development of the buoyancy system brings with it a myriad of technical challenges.

The DSR system has two distinct components: a buoyancy chamber (BC) and a gas generation unit (GG). The GG affords the opportunity to dispense with shipboard compressors and the concomitant complex manifold of connecting umbilical pipe work. It provides for a fully remote system eliminating all risk associated with extensive physical surface to sub-sea connection throughout the entire lift operation. Indeed as GGs (and BCs) can be towed through the water to the operational site, very little mandatory and potentially expensive actual deck space is required. Furthermore the system is fully scalable.

The design and development can initially be split into several components: structural design of the caisson, cryogenic system development, mechanical systems integration, and electrical and process control systems design. The rest of this paper addresses aspects of each of these issues.

STRUCTURAL DESIGN

In the design of a structure such as the DSR Buoyancy device, of paramount importance is the general arrangement of the vessel. Many concepts about the vessel are original; however, there are certain aspects of the design which must be considered carefully. As such the general arrangement for the DSR buoyancy system, illustrated in *Figure 1*, was generated.

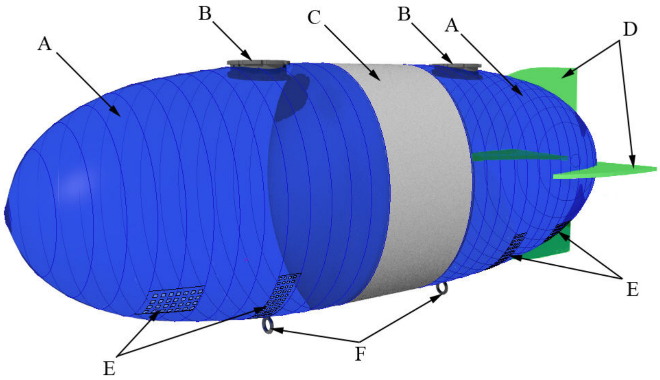

Figure 1: General arrangement of the buoyancy system

The main aspects of the design are labeled in *Figure 1:*

A. The two large buoyancy chambers at either end of the vessel. These are filled with gas and create the buoyancy which the device uses to lift or lower objects. In order to maintain acceptable levels of control of the system, these chambers will be linked through a small tube in order to equalize the pressure in each thus maintaining the attitude of the device.
B. The two main valves, each of which comprise of two parts: A larger 'blow out' valve for venting gas rapidly and controlling the tension in the lines to the payload once the stiction force with the seabed has been overcome, and a smaller valve integrated into the larger one which is for fine control and tuning of the amount of gas in the buoyancy chambers and hence the rate of ascent of the device and the payload.

C. The central part of the buoyancy device is the cryogenic dewar. The dewar holds the liquid nitrogen (LIN) at the ambient pressure. The cryogen is heated in two stages; initially it is given enough energy to increase the pressure in the dewar further and effectively pump the LN_2 out of the container, the liquid is then heated to the ambient temperature of the surrounding sea water before being released into the buoyancy chambers. This gasification process also provides a measure of buoyancy control alongside that of the top valves (B). The dewar is shorter and broader than conventional containers, with the axis parallel to that of the caisson. This results in the stronger domed ends providing much more effective structural support than in a slimmer structure. With its location and shape the dewar also provides much of the structural integrity in the central area of the vessel. The composite shells which make up the buoyancy chambers are bolted on to the dewar illustrating part of the modularity of the design, and thus enabling further refinement and development of the system to be achieved in an economic manner.

D. The fins towards the stern of the caisson provide directional stability when the system is operating in currents. They also prevent oscillations due to water moving around caisson during ascent.

E. The caisson has several openings towards the bottom of the buoyancy chambers so that the caisson can free flood. These openings also provide a measure of safety such that if the gasification system fails and cannot be halted, the excess gas will escape through the vents in the base preventing an explosion of the caisson. The vents have a grille over them in order to prevent ingress of sea life which could cause problems if they were able to access the buoyancy chambers.

F. There will be two attachment points for the line down to the payload in order to distribute loading over the caisson structure. These will be placed off the parallel mid body, towards the domed ends in order to take advantage of the increased structural integrity inherent in these regions. NB This is not illustrated in Figure 1 as it is difficult to show both the attachment points and the free flooding vents on the cross section.

It is intended that power for gasification is to be provided from a surface vessel by way of an umbilical cable. In the event that several buoyancy systems are required for an individual lift the power from the surface will run down to one 'lead' caisson from which it will be distributed to the other vessels thus limiting the amount of cabling required from the surface, preventing tangling and making system control more straightforward.

The size of the vessel is directly related to the amount of lift it is able to produce. In order to lift a payload of 30Te, the vessel must displace 30Te of seawater, plus the mass of any fixed structure that has a density more than that of seawater. As LIN has a density of 808kg/m^3, compared to the density of salt water at 1025kg/m^3, it is apparent that the LIN itself will provide a measure of buoyancy. An initial weight estimate was carried out for four different methods of constructing the buoyancy device in order to determine the operational depths a caisson of 9m in length and 3m in diameter could achieve. Type (1) is for a steel caisson, steel substructure, stainless steel dewar and conventional subsystems; type (2) is for a composite caisson shell, aluminum frames, stainless steel dewar and conventional subsystems; type (3) is for a composite caisson shell and frames, stainless steel dewar and conventional subsystems; type (4) is for a fully composite caisson, composite dewar and subsystems constructed from exotic materials. The results of this analysis are shown in Table 1.

Table 1: Results of the preliminary weight estimate

Caisson Assembly Type	Max. depth of operation (m)	Vol. of LN_2 for operation at max depth (l)	Vol. of LN_2 to operate at 350m depth (l)
1	430	4500	3519
2	545	5600	3280
3	730	7300	2962
4	1075	9950	2732

This weight estimate is carried out such that the wet weight of the caisson is estimated; including the amount of LIN required to lift a 30Te payload plus 50% to cover boil off and venting. The volume required for a dewar to contain the required amount of LIN is subtracted from that of the whole caisson to gain a measure of the buoyancy the vessel can be expected to achieve at a range of depths. It should be noted that many assumptions have had to be made in order to achieve this weight estimate as it is being made at a preliminary stage in the design cycle.

All of the different material combinations assessed will operate to a depth exceeding the design depth of 350m. It has, however, been decided that the structure is to be designed to be modular such that, in order to operate at greater depths, components may be interchanged at will. This incorporates the possibility of refining the design of different components and enabling them to be amalgamated into the main structure without the need for a complete, and expensive, rebuild. As such, despite the fact that a steel caisson would be able to function as a buoyancy device at the design depth, it is thought that construction the caisson shell and structure from composite materials would be the optimal solution in order to gain maximum performance from the device and promote design optimization in future.

In order to reduce build costs, especially at this early stage in the development of the buoyancy device, it may be necessary to reduce the size of the caisson. This would reduce the maximum depth at which the vessel would operate effectively, though not affecting its operation at the design depth of 350m. More so, the caisson is designed to be fully scalable and thus enlargement at a later stage in the development of the design should be relatively easy to facilitate.

ASCENT AND LIFT DYNAMICS

The theoretical basis for a mathematical model of the buoyancy response of the system has been derived as the start of a parametric representation of the system. Subsequently a system modeling approach based on Matlab-Simulink® will be used to build a complete model of the buoyancy response. Modeling of external fluid flow at the controlled speeds of ascent and impact of controlled gas release will need to be included.

The volume of each caisson, V_c, can be represented by:

$$V_c = \frac{\pi(L-D)D^2}{4} + \frac{\pi D^3}{6} \ , \qquad (1)$$

where L and D are length and diameter of the caisson respectively. For a caisson that is 9m long and 3m in diameter: $V_c = 56.6m^3$ therefore in sea water the gross lift for each caisson, L_c:

$$L_c = \rho_{SW} V_c$$
$$L_c = 58\text{t} \qquad (2)$$

The maximum depth of operation is 350m. With a proposed lifting speed of around 0.5m/s (1800m/h), once the payload is released from the sea bed it should take around 12 minutes at the design depth.

Breakout Force

The first step for a lifting process is to overcome the bottom mud suction force to allow the object to be lifted. As the local properties of the seabed vary and are thus difficult to define, it is generally very difficult to define exactly what the suction force is [3]. The suction force is time dependent. The loads will be immense if pulled instantly. With the buoyancy system, a constant load can however be applied over time and use of water jetting along the side of the object would also help the release form the seabed.

The initial estimation of bottom breakout force, however, can be made based on the studies of Vaudrey [4] where three formulae for calculating the breakout force were examined and three breakout force reduction methods tested using objects with difference geometry shapes (cylinder, sphere and block) of around 2 tonnes weight each. The main findings were that:

(1) without breakout force reduction the breakout ratio (Lift force required to breakout/object wet weight) was about 1.3 whereas;
(2) with reduction the breakout ratio was 1.04~1.08. So for the investigation at this stage, the lift force needed for breakout can be assumed to be of the form:

$$L_b = (1 + b_0)W \ , \qquad (3)$$

where L_b and W are the breakout force and the wet weight of the object respectively, whereas b_0 is a non-dimensional parameter depending on the properties of the object and the seabed and operation details.

Lift Dynamics

When only the motion in vertical direction is considered, the equation of motion of the system can be expressed as:

$$(M + m_a)\ddot{Z} + \frac{1}{2} C_D \rho_{SW} S_a \dot{Z}^2 = L - W \ , \qquad (4)$$

where M, m_a, Z, C_D, ρ_{SW}, S_a and L are the total mass, added mass due to sea water, caisson vertical position coordinate, drag coefficient of the system, sea water density, surface area of the system and lift force due to the buoyancy of the caissons.

Initially, the added mass m_a of the system can be estimated based on the data for two dimensional cross sections. As an approximation, the drag coefficient of the system can be calculated based on the ITTC skin friction formula with an estimated form factor or based on the drag coefficient in Morison's equation used in dynamical analysis of offshore structures. If deemed necessary at a later stage, more accurate predictions of these values can be incorporated in the equation.

Equation (4) can be solved following a time stepping approach using standard numerical schemes such as Runge–Kutta methods available in computer programs such as Matlab etc. The nonlinear nature of the equation and the time dependent parameters can also be accommodated in such a solution procedure.

Estimation of the Terminal Velocity

If a constant lift force is applied to the object to be lifted after breakout, the object will accelerate upwards since $L_b - W > 0$ as this is the value needed for breakout. The maximum velocity that can be reached is limited to:

$$\dot{Z}_T = \sqrt{\frac{2(L-W)}{C_D \rho_{SW} S_a}} \qquad (5)$$

But in a well controlled lift operation, this is not allowed to happen and in this case, the buoyancy needs to be rapidly reduced after breakout of the object from the seabed.

Immediately after breakout when the upward speed is still close to zero, the lift force reduction can be calculated when the limit on the allowable acceleration $\ddot{Z}_{\max}$ is specified where:

$$\Delta L = L - W - (M + m_a)\ddot{Z}_{\max} \qquad (6)$$

For an extreme case where $\ddot{Z}_{\max} = 0$, we have

$$\Delta L = L - W \qquad (7)$$

If $L = 1.1W$ then lift reduction will be 10% of the original lift applied during breakout.

If a desired ascending time history of the lifted object *Z(t)* is prescribed, equation (4) can be used to calculate the required variation of the lift which can then be used as an input to the control module of the system.

Example

Assuming the object to be lifted is of a cylindrical form, *D*=3m, *L*=6m, *V*=42m^3, *M*=70tonnes and *W*=265KN. In this case, the added mass and drag force due to water can be approximated by [5]:

$$m_a = 1.51\frac{\rho\pi D^2}{4}L, \qquad (8)$$

$$m_a = 66 \text{ ton}$$

and

$$F_d = 0.9\frac{\rho D}{2}L\dot{Z}^2. \qquad (9)$$

$$F_d = 8300\,\dot{Z}^2$$

In addition if $L = (1 + b_t)W$ where b_t is a function of time and at breakout point in time $b_t = b_0$. The equation of motion now takes the form:

$$1.36\times10^5\ddot{Z} + 8.30\times10^4\dot{Z}^2 = 2.65\times10^5\times b_t \qquad (10)$$

This equation can be re-written as:

$$\ddot{Z} + 0.610\dot{Z}^2 = 1.95b(t) \qquad (11)$$

So the terminal velocity is:

$\dot{Z}_T = 1.8\sqrt{a}$ and this can be tabulated as shown in *Table 2*:

Table 2: Table of Terminal Velocity

a	0.04	0.09	0.16	0.25
$\dot{Z}_T$ (m/s)	0.36	0.54	0.73	0.90

When *b(t)* is given, equation (11) can be used to obtain the time history of *Z(t)* as illustrated in *Figure 2*.

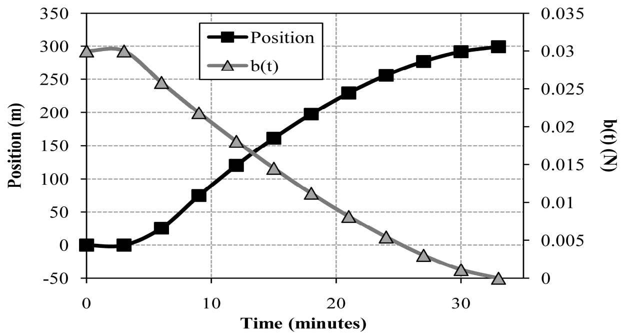

Figure 2: History of Z(t) for a depth of 300m and lift time of 30 minutes.

If the time history of *Z(t)* is prescribed as:

$$Z(t) = H\left[\sin^2\left(\frac{\pi t}{2T_l}\right) - 1\right] \qquad (12)$$

the required lift variations in terms of $b(t) = \frac{(L - W)}{W}$ can be found. This is illustrated in *Figures 3* and *4*.

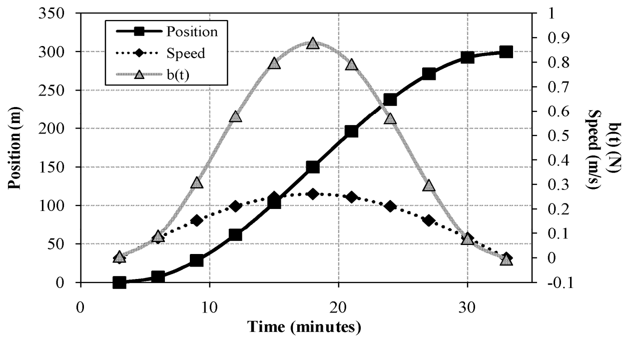

Figure 3: Illustration of position, rate of ascent and required lift variation against time for a depth of 300m and a time period of 30 minutes.

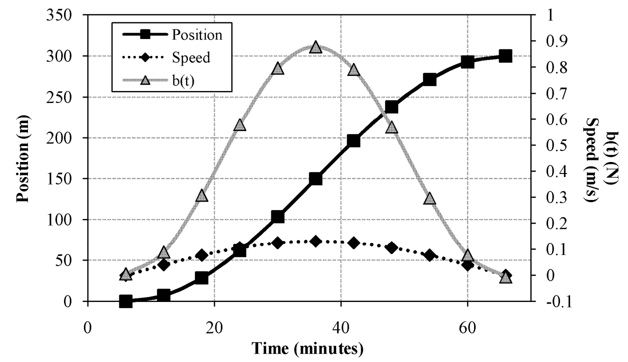

Figure 4: Illustration of position, rate of ascent and required lift variation against time for a depth of 300m and a time period of 1 hour.

HEAT EXCHANGE AND THERMO FLUID MODELING

Another aspect of the Buoyancy System design is that relating to the use of a cryogen to create gas which will fill the buoyancy chamber. Initial calculations as to the suitability of different gases to the process have been undertaken. Feasibility calculations of the operating requirements of the buoyancy chamber (caisson) have been carried-out, based on the thermodynamic data given in *Table 3* below. The calculations have been carried out with the aim of producing 1m^3 of gas in one minute.

The water in the chamber is to be displaced by gas generated from liquid stored in a cryogenic container (dewar). Alongside the results of the calculations for Nitrogen (N_2), *Table 3*, calculations have been carried out for Argon (Ar), Carbon Dioxide (CO_2), Helium (He), and Hydrogen (H_2). Of these cryogens, CO_2 was discarded as the operating temperature of the system is lower than the critical temperature of CO_2 the gas would need heating and insulating in order to be useful. Ar was also discarded as a possibility due to its greater density when compared to N_2 and hence in order to displace a volume, *V*, of seawater the mass of Ar required is approximately 1.5 times that of N_2. In the case of the buoyancy chamber, weight is an important design consideration and any method of decreasing the overall vehicle weight will directly increase the depth the chamber can operate at and also the lift capacity of the vehicle.

It should be noted that He is considerably more expensive than N_2 and is also a finite resource. He costs approximately £5 per liquid liter as opposed to £0.25 per liquid liter for N_2. H_2 tends to be **highly explosive** when mixed with the correct percentage of oxygen, and therefore if this were ever to be used then considerable care must be taken when the buoyancy chamber nears the surface. It is thought, however, that at depth H_2 could work very efficiently and effectively and safely. Both He and H_2 are considerably less dense than N_2 and thus produce a weight saving which could be beneficial at shallower depths, though imperative if the system is ever to try and operate at depths exceeding ~750m.

Table 3: Thermodynamic data for Nitrogen

N_2	P	Temp	ρ	H	S	Cv	Cp
	MPa	K	kg/m^3	kJ/kg	kJ/kgK	kJ/kgK	kJ/kgK
State 1	0.1	77	808.25	-122.83	2.8233	1.0686	2.0405
State 2	3.5	77	816.74	-120.43	2.8001	1.0753	2.0074
State 3	3.5	278	42.871	279.7	5.6838	0.75283	1.1085
			Change	*of*	*state*		
1 to 2	3.4	0	8.49	2.4	-0.0232	0.0067	-0.0331
2 to 3	0	201	-773.87	400.13	2.8837	-0.3225	-0.899

Nitrogen requirements for 1m3 water displacement:-
Initial liquid requirement at NTP = 50.8 ltr
Heater power for 1 m3 in 1 minute; (States 1 – 3) = 275.1kW
The water in the chamber will be displaced by 41.0 kg of N_2.

In the calculations it has been assumed that the fluids will be supplied in the liquid state within an (vacuum) insulated dewar, either in (State1) at their normal boiling points or at elevated pressure e.g. (State 2). Finally by the introduction of thermal energy the fluid will be transferred to the buoyancy chamber at 3.5MPa and 278K for displacement of the water (State 3). The findings of these calculations are summarized in *Table 4*. These represent ideal values.

Table 4: Summary of thermodynamic data

	N_2	Ar	He	H_2
Pressure (MPa)	3.5	3.5	3.5	3.5
Pressure (bar)	35	35	35	35
Initial liquid volume (l)	50.8	44	51.1	34.5
Power required for boil off in 1 minute (kW)	275.1	267	149.2	187.3
Mass of liquid (kg)	41.0	62	6.13	3.07

- Initial liquid volume required at NBP for 1m^3 of gas at the operating pressure
- Power required to displace 1m^3 of liquid in the caisson at the operating pressure within one minute
- Temperature at the operating pressures has been taken to be 5^{o}C (278K)

Solubility of gases

The buoyancy system is not going to have an internal bladder in which the gas is contained once it is produced at depth. Therefore the gas will have contact with the sea water in the buoyancy chambers.

The solubility of N_2 in sea water, especially at depth, could be a factor in the design of the buoyancy system. If the gas is highly soluble then there will be a reduction in volume and more gas will need to be generated in order to compensate for this. Letcher [6] discusses the solubility of gases in both water and sea water, although little information is available with regards to quantifying the solubility of N_2 in sea water.

Divers are susceptible to both nitrogen narcosis - where nitrogen dissolves into nerve membranes in the body at depth and causes a reversible alteration in consciousness - and the bends - where inert gases (mostly nitrogen) dissolve into the blood stream at deep depths or rather high pressures and when the diver rises without taking the required decompression stops bubbles form in the blood stream resulting in decompression sickness. Deep water divers do not use compressed air but substances that reduce the proportions of N_2 and O_2 below those of air, to allow the gas mixture to be breathed safely on deep dives. Helium is generally added to create a Trimix of the three gases which is varied in concentration with depth. This is due to the fact that He is considerably less soluble in the blood stream than other inert gases and therefore the diver is less susceptible to the bends and has to spend less time in decompression when returning from deep/elongated dives. Using this information, it is possible to infer that Nitrogen may also be significantly more soluble in sea water at depth (high pressure) when compared to Helium.

Gases dissolve in liquids to form solutions. At higher pressures gases are more soluble in liquids, although the opposite is true for lower temperatures. This dissolution is an equilibrium process for which there is an equilibrium constant, *K*. The form of the equilibrium constant shows that the concentration of a solute gas in a solution is directly proportional to the partial pressure of that gas above the solution. This is Henry's Law, first proposed in 1800, and it usually takes the form of the following equation:

$$p = K'_c\, c \qquad (13)$$

Where, p is the partial pressure of the gas, c is the molar concentration of the gas, and K'_c is the Henry's law constant on the molar concentration scale.

Henry's law is found to be an accurate description of the behavior of gases dissolving in liquids when concentrations and partial pressures are reasonably low. As concentrations and partial pressures increase, deviations from Henry's law become noticeable. This is similar to the behavior of gases, which are found to deviate from the ideal gas law as pressures and temperatures increase. Therefore it is not necessarily applicable to the solubility of N_2 at depth. The value of K'_c is different for every gas, temperature, and solvent.

It is expected that experimental testing using the hyperbaric chambers at the National Oceanography Centre (NOC), Southampton, could be beneficial in order to determine the value of K'_c for N_2 in sea water over a range of practicable temperatures. Thus determining the relative solubility of N_2 at depth and whether this could be a problem during caisson operation and as such will need to be considered during the design of the vessel.

It is intended that a block diagram of the system will be developed in Simulink® that represents the major heat flows between the constituent components: identifying conduction paths, convection and radiation effects. An analytical approach based on component size, mass and average thermal properties will allow rapid optimization of component sizing/position to be carried out.

PROCESS AND LIFT CONTROL MODELING

The necessary sensors, instrumentation, communication systems and expected response time will be investigated. A distributed approach to control over significant distances is required for a coordinated lift alongside the sensitivity of thermal control for controlled boil-off.

The initial work in this programme has commenced with a review of recent published work using Simulink for control. This complements the on-going use of this package in a real-time yacht fleet race virtual reality simulator, 'Robo-race'[7].

MATLAB® itself is a high level programming language released initially in the 1970's and developed ever since by Mathworks Inc. In the early 1990's the graphical programming interface Simulink was developed alongside Matlab. Simulink is an excellent environment for dealing with real-time control (and simulation thereof) of non-linear systems.

The graphical interface allows the complexity of the individual constituent components of a system to be individually developed as understanding improves. The initial work will consist of representing the simple lift model of the individual buoyancy system to be captured. Of interest is how the transition from no-motion to lifting motion is controlled as once the stiction of the seabed is overcome there will be an excess of buoyancy. The current method with an array of multiple buoyancy devices would be to release a sufficient number of these devices to reduce the buoyancy to a nearly neutral condition so that slow (controlled ascent) can be maintained. For large dry mass components, however, there is likely to be sufficient inertia within the system that it may be possible to use a valve system to release sufficient N_2 that buoyancy can be brought close to the neutral condition. It is in this area that the Simulink model will first be applied to the investigation. The first stage is to implement the one degree of freedom system equations obtained in the section on Ascent and Lift Dynamics, for a single prototype buoyancy device. A model for the rate of gas discharge through a typical valve will then be applied to give a time dependent equation for the lift:

$$\frac{dL}{dt} = \left(\dot{V}_{in} - \dot{V}_{out}\right)\left(\rho_{N_2} - \rho_{SW}\right) \tag{14}$$

where both the N_2 gas and sea water can be modeled as temperature dependent as well as local pressure within the caisson. The inflow rate will be determined by the capability of the gasification plant and the outflow by the valve diameter and pressure differential. The Simulink will represent each component and investigate time-scales for actual control.

The modularity of the system will allow additional complexity such as multiple buoyancy devices to be developed along with multiple degrees of freedom to investigate environmental impacts such as local marine currents as the work progresses.

In order to begin the modeling process, the system must be broken down into various aspects and each part considered. This process also provides an idea of what sensors will be required for certain tasks and lift control of each individual caisson and the lifting system as a whole.

Figure 5 illustrates an overview of a single caisson lift system. Essentially the control system has two modes:

1) To build tension in the line in order to over come the stiction force
2) Control the motion of the buoyancy system and target object (once released)

Where B is the buoyancy of caisson (N), M is the mass of caisson (kg), g is the acceleration due to gravity (m/s^2), T is the tension (N), b is the buoyancy of target object (N), m is the mass of target object (kg), S_t is the stiction force (N), V is the volume (m^3), V_i is the initial volume (m^3), t is the time (s), m_g is the mass of gas (kg), m_l is the mass of liquid nitrogen (kg) and m_f is the fixed structural mass (kg).

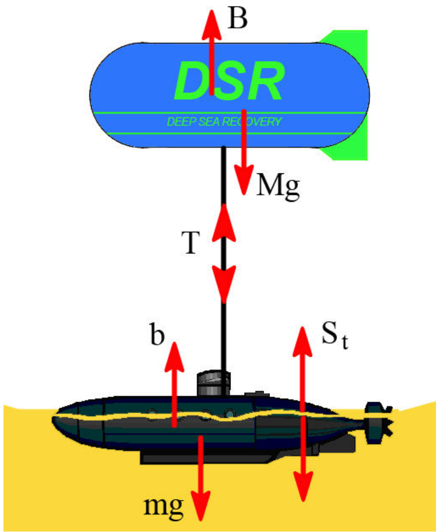

Figure 5: Single caisson system overview

We know that:

$$B = \rho_{H_2O} V g \quad (15)$$

And:

$$T = B - Mg \quad (16)$$

With:

$$V = V_i + \left(\frac{\partial V}{\partial t}\right)\Delta t \quad (17)$$

The total mass of the buoyancy system, *M*:

$$M = m_g + m_l + m_f \quad (18)$$

Combining equations 1.1-1.4 we get:

$$T = \left[\rho_{H_2O}\left(V_t - \frac{\partial V}{\partial t}\Delta t + \frac{\partial V_{in}}{\partial t}\Delta t\right) - \left(m_g - \frac{\partial m_{out}}{\partial t}\Delta t + m_l + m_f\right)\right] g \quad (19)$$

Equation (19) is represents a mass balance of a single caisson system. The $\frac{\partial V}{\partial t}\Delta t$ term represents a change in volume due to gas release from the upper valves and therefore water ingress in the bottom valves/openings. The $\frac{\partial V_{in}}{\partial t}\Delta t$ term represents the change in volume due to gas production, and is therefore directly related to the current in the heating element. The $\frac{\partial m_{out}}{\partial t}\Delta t$ term is the change in mass due to gas being released from the upper valves.

Required sensors

Several sensors will be required to monitor the aspect and position of both the buoyancy system and the target lift object during the recovery process. The following list is an overview of possible sensors and their use:

1) *Temperature* – this may be required to be monitored in several areas, these being the liquid nitrogen dewar, the gas in the buoyancy chamber and the ambient water temperature
2) *Tension* – in the line connecting the caisson to the target lift object to manage the lift process, and possibly a device on any umbilicals to prevent tightening
3) *Liquid level* – both of the LN_2 in the dewar and the sea water in the buoyancy chamber to assess the mass/volume of the system which can be input into the control algorithm
4) *Acceleration* – accelerometers on both the caisson and target lift object to assess the rate of ascent/decent
5) *Depth* – depth sounder on both the caisson and target lift object to monitor the depth of each, possibly multiple gauges in order to control the aspect of each object in 3D space
6) *Pressure* – of the surrounding fluid, the gas in the buoyancy chamber, and the gas in the cryogenic dewar for accurate calculations and control and also as a method of monitoring safety aspects of the design and preventing implosion/explosion
7) *Structural stresses* – load cells on the target lift object in order to assess stresses and strains and hence structural integrity during the lift

These measurements will be compiled into four main component systems:

1) Outlet valves – which control the mass flow rate of gas out of the buoyancy chamber
2) Gasification plant – controls the manufacture of nitrogen gas and hence the mass flow rate of gas into the buoyancy chamber
3) Flooding system/valves – controls the rate of descent/flooding in the buoyancy chamber
4) Safety systems – fail safes put in place to monitor the situation and prevent catastrophic events.

Whole system

These requirements obviously have to be brought together in a complete system of control vessel, multiple buoyancy devices, and a target lift object. *Figure 5* illustrates a schematic of this situation.

In this complete system:

- The control vessel monitors and controls all caissons relative to one another, communicating with each if alterations of rate of ascent/descent, trim, and position are required from one caisson to affect the system as a whole.
- Each individual caisson has a simple low level central control which maintains local systems such as local trim, pressure, rate of gasification etc.

The attitude of the rising submerged body is monitored remotely by the control vessel and this information relayed to the lower level controls in each caisson.

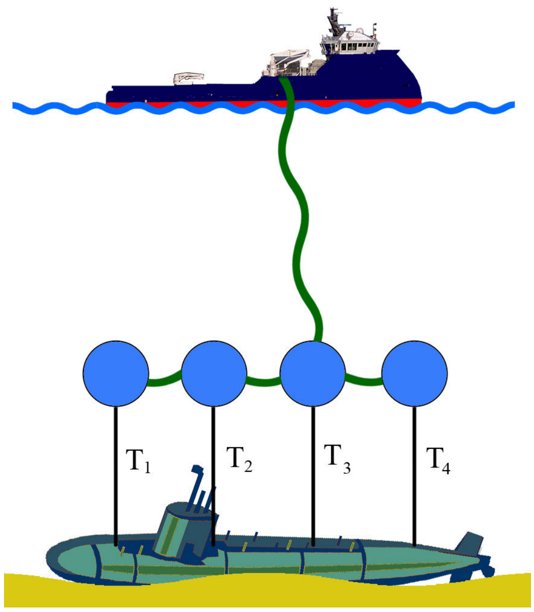

Figure 6: Overview of the whole system

CONCLUSIONS

The concept design for a deep sea recovery buoyancy system which uses novel technology in order to lift and lower objects in the ocean in a controlled manner has been discussed. It is apparent that a structure which is modular lends itself to further development in the most economical manner. A general arrangement for the vessel has been illustrated and the main concepts behind the operation discussed. In these opening stages of the design of the buoyancy system, it is intended that operation at a depth of 350m be proved. In future, however, greater depths of operation are proposed.

A key factor regarding the increase in operational depth for the buoyancy system is reduction in weight. This is illustrated in the weight estimate – where the lightweight, composite caisson utilizing bespoke subsystem components constructed from exotic materials has the possibility to operate at depths exceeding 1000m.

One manner in which to reduce weight would be the use of a less dense cryogen, however this would not be without considerable cost and possibly risk due to the scarcity of certain elements, and the volatile nature of others. Therefore it has been decided that LIN would be the most effective, safe, and economically viable cryogen to use for the buoyancy system.

Other areas of operation of the buoyancy system have been considered. The mathematical modeling of the process control, and the ascent and lift dynamics of the system has been achieved and it is intended that this now be used as the basis of a numerical model in MATLAB Simulink®. This model will then be coupled with Computational Fluid Dynamics to gain an accurate representation of the behaviour of the recovery system in operation.

NOMENCLATURE

b	N	Buoyancy of payload
b_t	-	Time varying breakout parameter
b_0	-	Non-dimensional breakout parameter
$b(t)$	(N)	Required lift variation through time
c	mol	Molar concentration of the gas
g	m/s^2	Gravitational constant
m	kg	Mass of payload
m_a	kg	Added mass due to sea water
m_f	kg	Fixed structural mass
m_g	kg	Mass of gas
m_l	kg	Mass of liquid
m_{out}	kg/s	Mass flow rate out of the caisson
p	Pa	Partial pressure of gas
t	s	Time
B	N	Buoyancy of caisson
C_D	-	Drag coefficient of the system
C_v	kJ/kgK	Specific heat capacity at constant volume
C_p	kJ/kgK	Specific heat capacity at constant pressure
D	m	Overall diameter of caisson
F_d	N	Drag Force
H	kJ/kg	Enthalpy
K'_c	-	Henry's law constant
L	m	Overall length of caisson
L_b	N	Breakout force
M	kg	Total mass of caisson
P	Pa	Pressure
S	kJ/kgK	Entropy
S_a	m^2	Surface area of system
S_t	N	Stiction force
T	N	Tension
$Temp$	K	Temperature
V	m^3	Volume
V_c	m^3	Volume of caisson
V_i	m^3	Initial volume
$\dot{V}_{in}$	m^3/s	Volume flow rate in
$\dot{V}_{out}$	m^3/s	Volume flow rate out
W	N	Wet weight of payload
Z	m	Vertical position of the caisson
$Z(t)$	-	Ascending time history
$\dot{Z}$	m/s	Rate of ascent of caisson
$\dot{Z}_T$	m/s	Terminal caisson velocity
$\ddot{Z}$	m/s^2	Acceleration of caisson
$\ddot{Z}_{\max}$	m/s^2	Maximum allowable acceleration
ρ	kg/m^3	Density
ρ_{N_2}	kg/m^3	Density of nitrogen gas
ρ_{SW}	kg/m^3	Density of salt water

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The Technology Strategy Board is a business-led executive non-departmental public body, established by the government. Its mission is to promote and support research into, and development and exploitation of, technology and innovation for the benefit of UK business, in order to increase economic growth and improve the quality of life. It is sponsored by the Department for Innovation, Universities and Skills (DIUS). Please visit www.innovateuk.org for further information.

REFERENCES

[1] Gores, J.N., *Marine Salvage*, David & Charles (Publishing) Limited, 1972, Great Britain, ISBN 0 7153 5454 X.

[2] Byrd, R.C., Velazquez, E.R., *State of the Art Removing of Large Platforms Located in Deep Water*, in the *Offshore Technology Conference*, 30th April – 3rd May 2001, Houston, Texas, U.S.A.

[3] Sawicki, A. and Miercyznski, J. (2003) *Mechanics of the breakout phenomenon*, Computers and Geotechnics Vol. 30, pp231-243.

[4] Vaudrey, K.D. (1972) *Evaluation of bottom breakout reduction methods*, Technical Note N-1227, Naval Civil Engineering Laboratory, Port Huneme, Ca.

[5] Barltrop, N.D.P. and Adams, A.J. (1991). *Dynamics of fixed marine structures*. Butterworth-Heinemann (3rd Edition). pp. 307-314

[6] Letcher, T. (Ed), *Development and Applications in Solubility*, Chapter 6 The Solubility of Gases in Water and Seawater, 2007, ISBN: 978-0-85404-372-9

[7] Scarponi, M., Conti, P., Shenoi, R.A. and Turnock, S.R. (2007) *Including human performance in the dynamic model of a sailing yacht: a matlab-simulink based tool*. In, *Modern Yacht, Southampton, UK, 11-12 Oct 2007*. London, UK, The Royal Institution of Naval Architects, 143-156.