A variable buoyancy system for deep ocean vehicles

M. Worall BEng, PhD, AMIMechE, A. J. Jamieson BSc, PhD, A. Holford BSc, R. D. Neilson BSc, MSc, PhD, M Player MA, DPhil(Oxon), CEng, MIEE, P. M. Bagley BSc, PhD, CEng, MIEE.

Abstract— **A variable buoyancy system has been developed for underwater vehicles operating deep in the ocean. This paper reports on the design, testing and development of the system. The system was designed to change buoyancy at up to 1 l/min at a depth down to 6000m. The results showed that the system worked at its design specifications after modification but that friction losses resulted in a relatively low efficiency of around 35% at low working depth, but efficiency increased with increasing depth to about 70% at 6000m. Efficiency could be increased further with redesign or with changes in specification.**

Index Terms— **AUV, ROV, variable buoyancy, variable ballast**

I. Introduction

A variable buoyancy system has been developed at Oceanlab, to provide low cost, low power consumption, regenerative variable buoyancy capability for underwater vehicles operating deep in the ocean. A prototype was commissioned and built. This was tested and a large-scale system was then designed. This paper describes the design of the large scale system, results of tests carried out and modifications made to improve performance.

II. Background

Oceanlab use autonomous scientific instrument packages called landers that are deployed from a surface vessel and descend to the sea floor. Experiments are carried out and then the lander is retrieved by shedding ballast [1]. A VBS was first considered so that a lander could be retrieved without having to shed ballast, could hover in mid-water and soft land on the seabed, and so minimize disturbance. Jamieson [2] describes the development of the concept and its application to lander technology. A low power, compact variable buoyancy system could also benefit underwater vehicles, especially unmanned underwater vehicles. Patent No WO2005019021 [3] reveals a variable buoyancy device for controlling the buoyancy of unmanned underwater vehicles such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). ROVs are used extensively for the exploration of the ocean in the scientific sector, for inspection, maintenance and construction in the oil and gas industry and for remote intervention and surveillance in the military sector. ROVs are controlled and powered from the surface through an umbilical cable and need extensive on-board logistical support from a field service vessel (FSV). A ROV generally controls its position in the water column and lifts or lowers payloads by using vertical thrusters. When seawater properties vary from site to site, or a change of tooling is required, the ROV may require trimming to maintain slight positive buoyancy and level attitude. This can be time consuming and is usually done manually by lifting the ROV out of the water and changing or shifting ballast. A variable buoyancy capability could enable a ROV to control its position, manipulate payloads and trim a vehicle in the water. An AUV is a robotic vehicle that is powered from on-board sources and controlled using pre-programmed mission profiles. The vehicle does not require logistical support except for deployment and retrieval. The energy source is limited [4] and so its functions are restricted mainly to observation, inspection, and surveying. An AUV is generally neutrally buoyant and moves vertically by lift generated from control surfaces as it moves forward. The limited energy source constrains the range of the vehicle and its data gathering capacity. Energy that is consumed in propelling and steering the AUV reduces the data that can be obtained. A variable buoyancy capability could enable AUVs to use energy more efficiently and enhance its functionality.

A prototype VBS was designed, built and tested at Oceanlab. The results and conclusions were described by Worall *et al* [5]. Fig. 1 shows a photograph of the prototype

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M. Worall is with Oceanlab, The University of Aberdeen, Newburgh, Aberdeenshire, Scotland, AB41 6AA, (phone: +44(0)1224 274412; fax: +44(0)1224 274402; e-mail: m.worall@abdn.ac.uk).

A. J. Jamieson is with Oceanlab, The University of Aberdeen, Newburgh, Aberdeenshire, Scotland, AB41 6AA (phone: +44(0)1224 274447; fax: +44(0)1224 274402; e-mail: a.jamieson@abdn.ac.uk).

A. Holford is with Oceanlab, The University of Aberdeen, Newburgh, Aberdeenshire, Scotland, AB41 6AA (phone: +44(0)1224 274412; fax: +44(0)1224 274402; e-mail: a.holford@abdn.ac.uk).

R. D. Neilson is with the Engineering Department, The University of Aberdeen, Kings College, Aberdeen, Scotland, AB24 3FX (phone: +44(0)1224 272797; fax: +44(0)1224 272497; e-mail: r.d.neilson@abdn.ac.uk).

M. Player is with the Engineering Department, The University of Aberdeen, Kings College, Aberdeen, Scotland, AB24 3FX (e-mail: m.player@abdn.ac.uk).

P. M. Bagley is with Oceanlab, The University of Aberdeen, Newburgh, Aberdeenshire, Scotland, AB41 6AA (phone: +44(0)1224 274408; fax: +44(0)1224 274402; e-mail: p.bagley@abdn.ac.uk).

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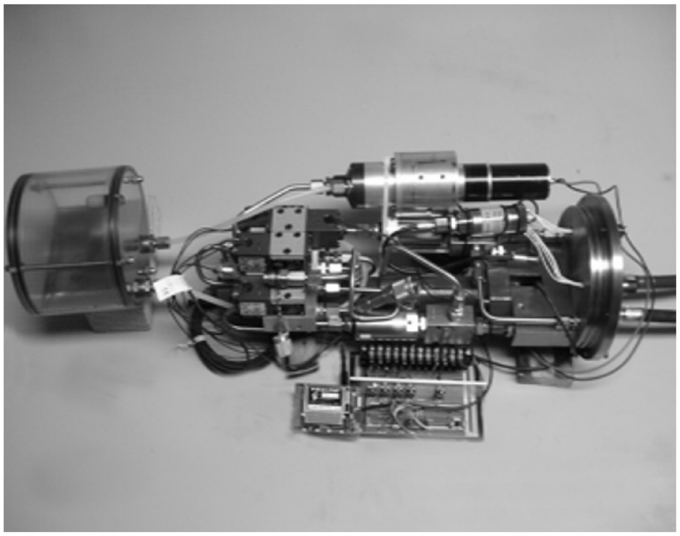

Fig. 1. Prototype VBS

VBS. It consisted of an axial piston hydraulic pump driven by a 120W dc motor and actuating a single acting pressure intensifier. It was designed to operate at an ambient pressure of up to 300bar. The system was tested using a flow control valve to produce back-pressure and so simulate ambient pressure. Tests showed that the efficiency of the system was approximately 80% and flow was 80 cm^3/min at a maximum back-pressure of 300bar. It was concluded that the system worked efficiently but the flow was only be suitable for small changes required for systems such as buoyancy engines that are used in profiling drifters and gliders [6]. A higher specification system was then developed from the prototype design that would be suitable for underwater vehicles.

III. System Description

A list of capabilities was drawn up from the conclusions from the tests on the prototype and market surveys carried out in the ROV, AUV industry.

Key capabilities:

- Compensate for picking up and dropping off loads
- Control descent and ascent
- Anchoring on seafloor
- Compensating for salinity, density and pressure variations
- Emergency release and recovery
- Docking and construction manoeuvres
- Bolting on to existing submersibles
- Autonomous of user controlled

System specification:

- 6000m depth rated
- 30kg buoyancy capability
- 1 kg/min buoyancy change
- 1.5 kW power consumption
- 75 Ah capacity for 3 cycles
- Regenerative
- Off-the-shelf components

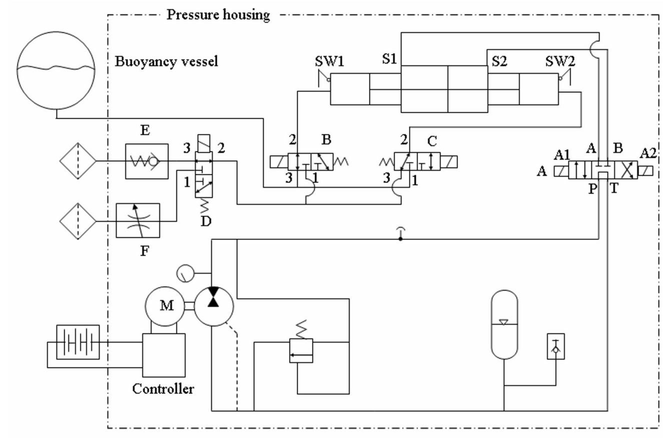

Fig. 2. Regenerative VBS circuit diagram

Fig. 2 shows a circuit diagram of the VBS and fig. 3 shows a photograph of the system in its pressure housing. The system has two modes of operation. In pumping mode, the VBS pumps seawater from a buoyancy vessel to the ambient so that buoyancy can be increased. In regeneration mode, a buoyancy vessel is filled from the ambient via the VBS, decreasing buoyancy but extracting some of the energy. An embedded microcontroller is used to control pump speed and valve sequencing. The microcontroller is also used to log data from transducers that measure motor voltage, battery voltage, motor current, hydraulic pressure, ambient pressure and pump speed. The VBD can be run autonomously by pre-programming the microcontroller with a mission profile or it can be controlled in real-time through an RS232 connection. All of the components are pressure sensitive and so are enclosed in a single pressure housing. The pressure housing is 0.4m inside diameter, 0.46m outside diameter, 0.25m in length and the material of construction is grade 5 titanium. Two 6000m rated glass hemispheres are used as end-caps to minimize weight and cost.

A. *Pumping mode*

When an increase in buoyancy is required, hydraulic fluid is pumped around a circuit by an axial piston pump/motor. The pump/motor is driven by 24v dc permanent magnet motor and its speed controlled by a four quadrant controller. Motor speed

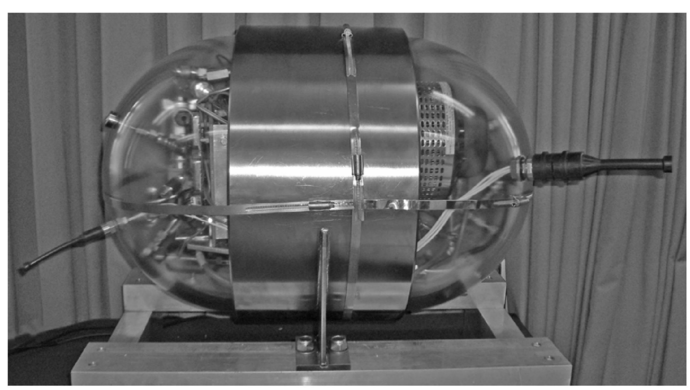

Fig. 3. Regenerative VBS photograph

is proportional to the voltage across it and is controlled by chopping the frequency of the supply. The four quadrant controller also allows a dc motor to be controlled in four modes, two modes are motor forward and reverse, and the other two are generator forward and reverse. The microprocessor is programmed to allow a selection of motor speeds from seven discrete speed settings that are in proportion to the supply voltage. Valve A is a four way three position valve that allows fluid to flow back to the return side in its neutral position and has two positions to actuate the pressure intensifier. Solenoids in valve A are energized alternately to direct flow to the pressure intensifier. The pressure intensifier is the interface between hydraulic and seawater circuits and multiplies the pressure in a 4:1 ratio so that pump/motor and VBS specification are matched and standard hydraulic components can be used. If solenoid A1 is energized, the flow path is from the pump/motor to port P and through port A to service port S1 in the pressure intensifier. A pressure difference builds up across the pressure intensifier and hydraulic fluid flows from the other side of the piston through service port S2, to port B and port T and back to the return side of the pump/motor. Motion of the piston causes seawater to be pumped out of the right side of the intensifier and through valve C, valve D and non-return valve E. Seawater is drawn from the buoyancy vessel through valve B and enters the pressure intensifier to the right. When the piston in the intensifier reaches the end of its stroke, an inductive sensor SW2 detects it, valve A1 is de-energized and valves A2, B and C are energized. The piston moves to the left causing water to be pumped out to ambient from the left hand side and drawn in from the buoyancy tank to the right hand side. When the piston reaches the end on its stroke, inductive sensor SW1 detects it, solenoids A2, B and C are de-energized, and solenoid A1 is energized, repeating the cycle. The actuation of the piston in the intensifier continues until the required volume of water has been pumped from the buoyancy tank. An accumulator stores excess fluid so that leakage can be compensated for and enables the hydraulic system to operate in a closed circuit. The pressure relief valve protects the circuit from excessive pressure. A non-return valve E prevents flow through valve E when valve D is off. The system is filled through a quick-connect coupling, and air is removed from the system by a bleed nipple.

B. *Regeneration mode*

When a decrease in buoyancy is required, valve D is opened and pressure from the ambient flows through a filter and metering valve F. If valve A is in its neutral position, the path to the circuit is shut off and the piston in the pressure intensifier will not move. If leakage should occur then the piston will only move to the end of its stroke, and so there will be no flow to the buoyancy tank. If solenoid A1 is energized, then seawater flows past valve C and acts on the right side of the pressure intensifier, building a pressure difference across it. Pressure builds up in the hydraulic circuit and hydraulic fluid flows from service port S1 and on to port A and P. At the same time a path is opened to service port S2 through ports B and T. Seawater flows from the left hand side of the pressure intensifier through valve B and on to the buoyancy vessel due to the motion of the piston. A pressure difference across the pump/motor and flow produces a torque, which drives the dc motor and generates an electric current. The four quadrant controller allows the dc motor to be used as a generator and to charge the 24v dc battery pack. When the piston in the pressure intensifier reaches the end of its stroke, inductive sensor SW1 detects it, solenoid A1 is de-energized and solenoid A2 is energized. Solenoids in valves B and C are energized so that paths are opened from ambient to buoyancy tank. Seawater from ambient enters the left hand side of the pressure intensifier through valve B. Seawater from the right hand side of the pressure intensifier flows through valve C and on to the buoyancy vessel. With solenoid A2 energized, hydraulic fluid flows from port S2 and through port B and P and on to the pressure side of the hydraulic circuit. Hydraulic fluid from the return side of the pump/motor flows through port T and A and on to service port S2. When the piston reaches the end of its stroke SW2 detects it, Solenoid A2, and valves B and C are de-energized and solenoid A1 is energized, thus repeating the cycle until the required amount of seawater has entered the buoyancy tank.

IV. Results

Tests were carried out to determine the performance of the VBS

A. *Test schedule*

Preliminary tests revealed that a compressed air supply would be needed to pressurize the buoyancy vessel in order to overcome suction losses, and a time delay would be needed to enable the intensifier to enhance the filling at the end of each stroke.

The system was operated at varying ambient pressures, simulated by creating back-pressure with a high pressure flow control valve. Each test was run for 20 minutes during which the flow was measured in a number of ways. The volume pumped on each stroke was measured by a 100cm^3 measuring vessel. The time taken to pump 1000cm^3 was recorded every 5 minutes so that any variation in flow could be determined during the test due to a reduction in battery voltage. The total volume pumped was recorded after each test. During each test, measurements of battery voltage, motor voltage, motor speed, hydraulic pressure and ambient pressure were logged at regular intervals so that variations in values could be observed over the test period. After each test the battery pack was recharged so that all of the tests started at approximately the same battery voltage. The ambient pressures simulated ranged from 0bar to 600bar in 100bar intervals.

B. *Test results1*

Fig. 4 shows how work in (W_{in}), work out (W_{out}) and efficiency (η) change with back-pressure.

At 0bar back-pressure, the pressure required to actuate the

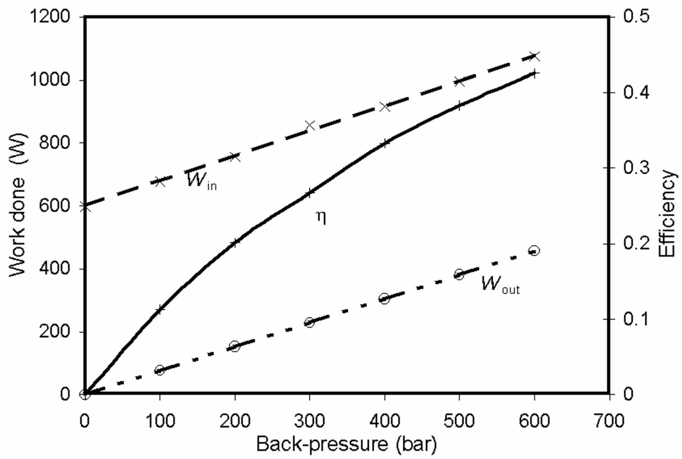

Fig. 4. Variation in work in, work out and efficiency with back-pressure. Motor speed, time delay and air pressure were 1000rpm, 2s and 2bar, respectively.

pressure intensifier and overcome friction was approximately 50bar and the work done was approximately 600W. There was a loss of approximately 20bar across valve A and losses of about 5 bar each across valves B, C and D. The pressure ratio of the pressure intensifier also results in a four to one flow ratio. At a pump speed of 1000rpm, a pump capacity of 4.9cm^3/rev, and a pump efficiency of 95%, volume flow was approximately 4.7l/min. The nominal flow from the VBS, assuming full swept volume and zero time delay should be 1.16l/min. However, the average volume flow was measured at 0.3l/min. The volume discharged during each stroke was approximately 31cm^3 compared with a swept volume of 72cm^3, therefore there was a 57% reduction in discharge volume per stroke. A time delay of 2 seconds, necessary to fill the cylinder to 31cm^3 also reduced the average flow. The 57% reduction in volume discharged was due mainly to restrictions in flow on the suction side by valves B and C. Valves B, C and D were chosen because they were suitable for use in seawater systems and were rated to over 600bar.

Tests were carried out at higher air pressures and with longer time delays. It was found that for the same air pressure, the average flow was approximately the same, whatever the time delay. For the same time delay, volume discharged increased with increasing air pressure. Fig. 5 shows the change in volume discharged with air pressure. It can be seen that almost full cylinder volume is discharged when air pressure of 3bar is applied. However, it was thought that a pressurized tank on-board an underwater vehicle would be undesirable or would compromise safety. Tests were completed at an air pressure of 2bar and a time delay of two seconds. At a back-pressure of 100 bar, the work in was approximately 670W, the work out was approximately 76W and efficiency was 11%. At 600bar back-pressure, work in was 1000W, work out 450W and efficiency 45%. At 600bar back-pressure, the average volume flow was approximately 0.3 l/min showing that the capacity was the same for varying back-pressures. The low efficiency was mainly due to the reduced stroke volume, time delay, and pressure losses in the system. Modifications were made to address the pressure losses on the suction side of the seawater system so that efficiency could be increased, and time delays and the need for a compressed air supply could be eliminated.

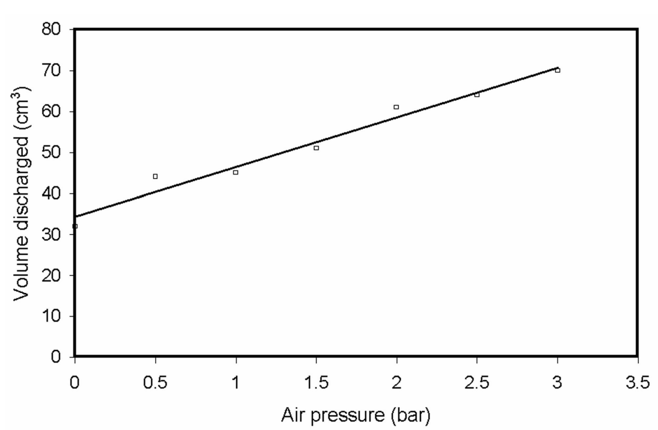

Fig. 5. Variation in volume discharged from single stroke of intensifier with increasing air pressure. Time delay two seconds at end of each stroke.

C. *Modified design*

Fig. 6 shows a circuit diagram of the modified VBS. A glossary of the graphic symbols used is given in Table I of Appendix A. The main difference with the previous design is the elimination of valves B and C in fig. 2 and their replacement with a number of check valves. Unfortunately, the replacement of valves B and C meant that there was no active direction control on the seawater side and so the regenerative function was eliminated. It was concluded that simple modifications could increase efficiency, but more complex modifications would be required to include a regenerative capability.

When negative buoyancy is required, water is pumped from the buoyancy tank to the ambient. As in the previous version, a 24v dc motor drives a hydraulic pump. Fluid is pumped around the circuit and when the pressure intensifier is required to be actuated, solenoids A1 or A2 are energized. If A1 is energized, fluid flows through port P to A and on the port S1. Fluid on the return side flows from port S2 to port B and T. The piston moves to the right, drawing in water from the

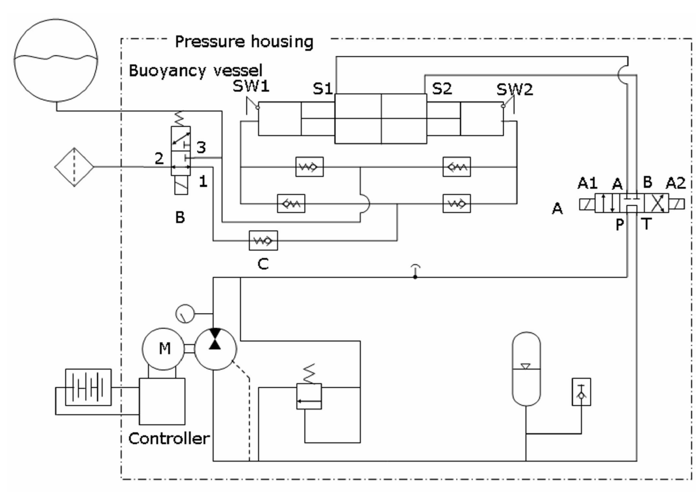

Fig. 6. Modified VBS circuit diagram

buoyancy tank on the left hand side and pumping water out to ambient on the right hand side. Four check valves are arranged in a circuit to enable flow to be directed to suction and pressure sides whichever direction the piston is traveling. As the piston reaches the end of its stroke, an inductive sensor detects it, A1 is de-energized and A2 is energized. Pumping continues as the piston travels in the opposite direction. When positive buoyancy is required, valve B is energized, and flow from ambient is diverted past non-return valve C to the suction side of the check valve circuit. Water flows to the buoyancy tank, bypassing the pressure intensifier, thus free flooding the tank.

D. Test results 2

Fig. 7 describes the performance of the system as back-pressure is varied. At 0bar back-pressure, the hydraulic system operated at approximately 50bar in order to overcome friction losses in the system and the average flow was measured at 1.1 l/min. This compares with a 50bar pressure loss and an average flow of 0.3l/min for the previous version. Time delays or compressed air were not required and full swept volume was achieved on each stroke. This showed that suction side pressure losses were negligible compared with the previous design. Friction losses on the pressure side were found to be similar to the results described in fig. 4 despite the elimination of valves B and C because volume flow had more than trebled. Pressure losses remained approximately constant as ambient pressure increased, so that efficiency was low because of the proportionally high losses. Efficiency increases as ambient pressure increases, from 32% at 100bar to 71% at 500bar. The work done by the hydraulic system increased from 520W at 0bar to 1300W at 500bar. Low efficiency is due mainly to friction losses in both the hydraulic and seawater circuits. The system was tested without valve B to evaluate individual pressure drops. The pressure required by the hydraulic system to pump water at 0bar ambient pressure was approximately 30bar, and so valve B was causing a 20bar pressure drop. Further modifications to the design could increase the efficiency of the system. A direction control valve with lower friction losses could reduce pressure drop in the hydraulic circuit and increasing the tube bore by upgrading the piping system could further reduce pressure drop. Fig. 8 shows how motor speed (n) and average volume flow (V_{ave}) vary with back-pressure. As back-pressure increases, the current draw increases causing a voltage drop across the VBS. Pump speed is controlled by varying the voltage across the electric motor in discrete proportions of the total voltage and so speed decreases, causing the average volume flow to decrease. Fig 8 shows that average volume flow and speed decrease from 1.42l/min and 1160rpm at 0bar back-pressure to 1.16l/min and 920rpm at 500 bar back-pressure. This shows that a flow of over 1 l/min is achieved over the design pressure range and this is because of the control of motor speed.

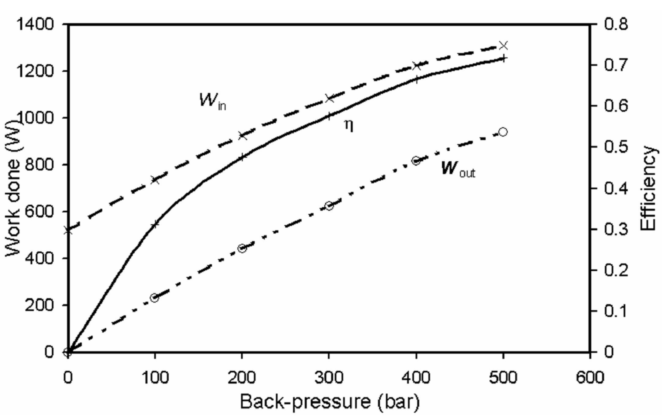

Fig. 7. Variation in work in, work out and efficiency with back-pressure.

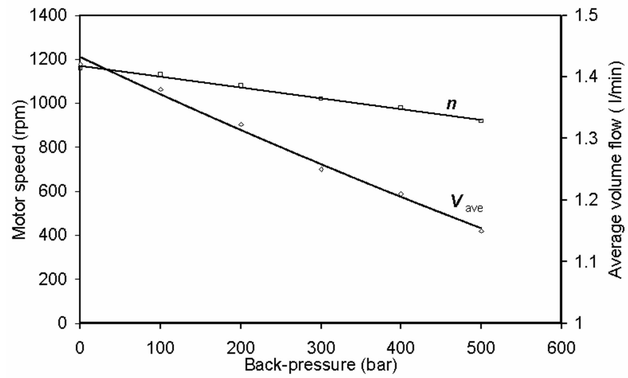

Fig. 8. Variation in motor speed and average volume flow with back-pressure.

V. DISCUSSION

The system has been specified to operate at a depth of up to 6000m and to pump water out of a ballast tank at up to 1 l/min. The specifications led to the selection of the hydraulic pump/motor, dc motor and the design of the pressure intensifier. The hydraulic pump/motor had the lowest capacity that could be sourced and so the minimum pump speed and intensifier area ratio determined the pressure and flow characteristics of the system. If regeneration was not required then a lower capacity pump could be sourced with reduced flow for a given speed, enabling the intensifier to be redesigned with a lower area ratio, so reducing its size and weight. A reduction in flow would also decrease pressure losses in valves and pipework. If a regenerative function were

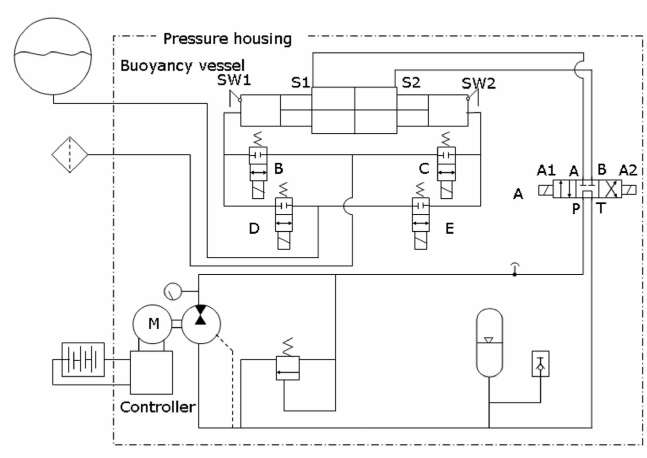

Fig. 9. Circuit diagram of modified VBS with regeneration

to be required then a more complex seawater valve arrangement would be required. Fig 9 shows how this could be implemented with simple off-the-shelf components. The check valve arrangement is replaced with four two way two position normally closed solenoid actuated spring return valves so that flow between the pressure intensifier, buoyancy vessel and ambient can be controlled. The microprocessor will control the valve sequencing so that seawater can be pumped from buoyancy tank to ambient, or from ambient to buoyancy tank via the pressure intensifier. Standard off-the-shelf valves can be sourced for ambient pressures of up to 300bar, but higher pressures would require specially designed and built valves.

VI. CONCLUSIONS

The system is simple in construction and operation, and it is easily modified to meet different user requirements. The results showed that the system worked at its design flow, but with excessive friction losses resulting in a relatively low efficiency. Efficiency was increased by modifying the system, but could be increased further by redesign and change in system specification.

APPENDIX A

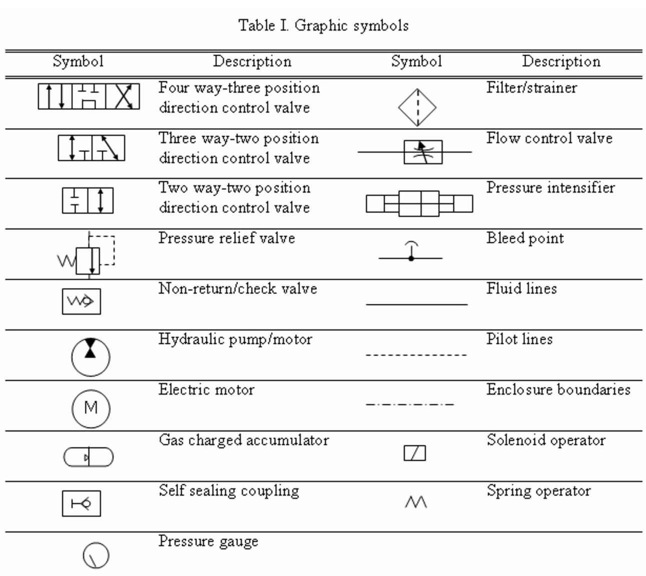

Table I. Graphic symbols

Symbol	Description	Symbol	Description
	Four way-three position direction control valve		Filter/strainer
	Three way-two position direction control valve		Flow control valve
	Two way-two position direction control valve		Pressure intensifier
	Pressure relief valve		Bleed point
	Non-return/check valve		Fluid lines
	Hydraulic pump/motor		Pilot lines
M	Electric motor		Enclosure boundaries
	Gas charged accumulator		Solenoid operator
	Self sealing coupling		Spring operator
	Pressure gauge		

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