

- [54] **MARINE SEISMIC CABLE BUOYANCY
SYSTEM**
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- [73] Assignee: **Esso Production Research Company**,
Houston, Tex.
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[51] **Int. Cl.** B63b 21/56, H01b 7/12, G01v 1/16
[58] **Field of Search** 340/7 PC; 114/16 E, 235 B;
174/101.5

[56] **References Cited**
UNITED STATES PATENTS

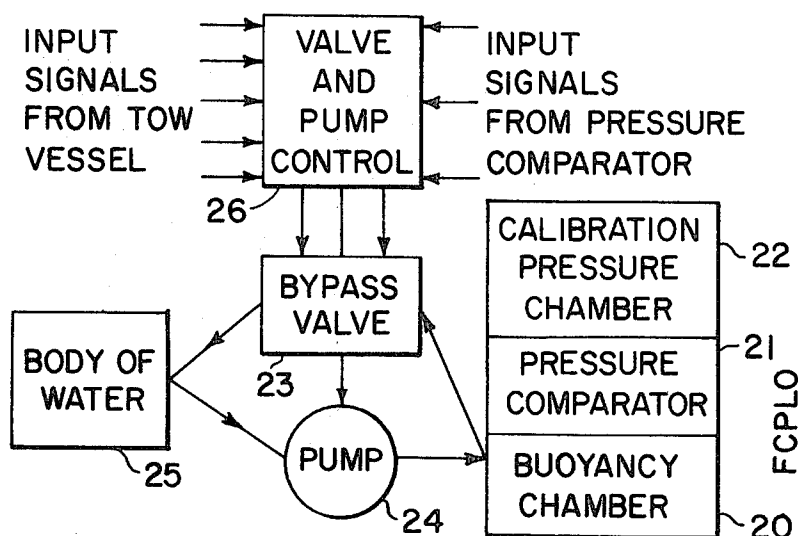
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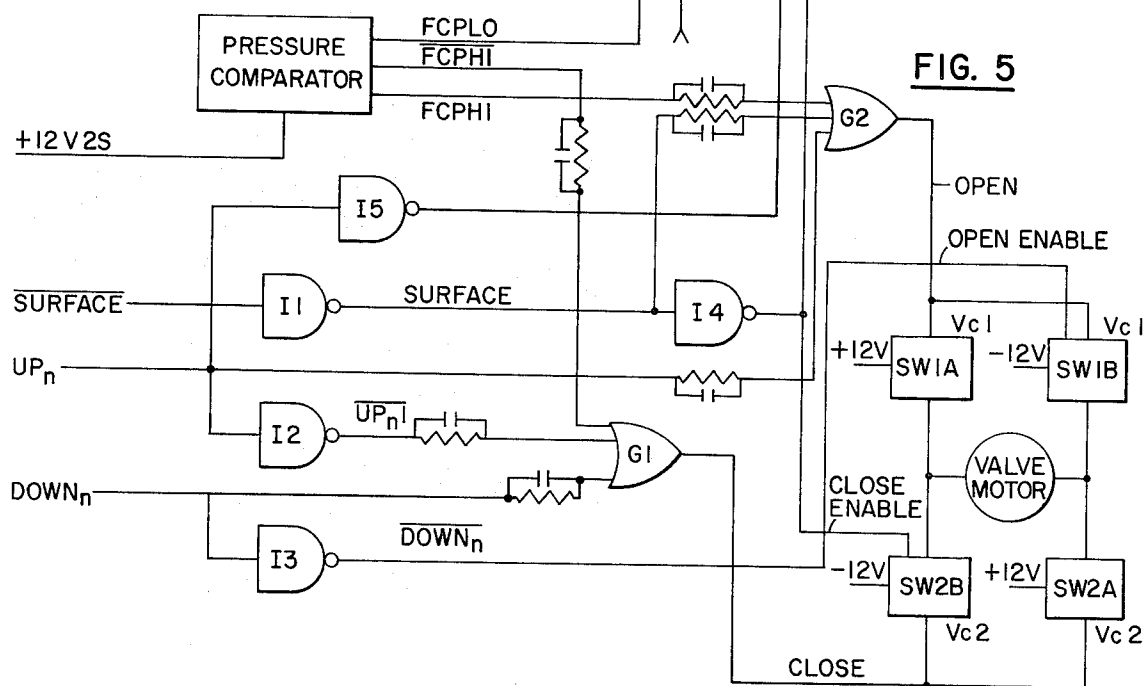
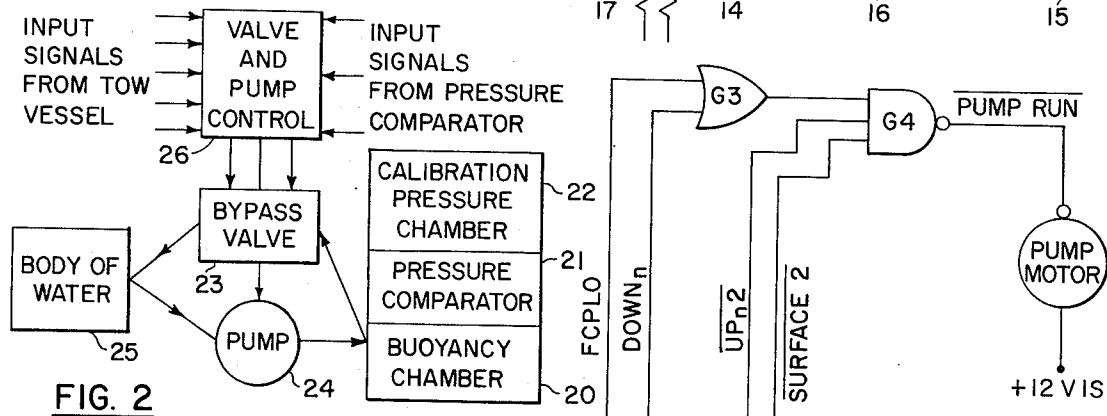
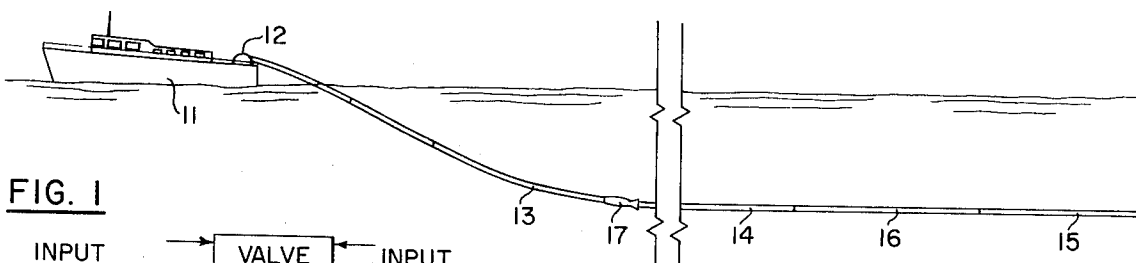
Primary Examiner—Maynard R. Wilbur
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[57] **ABSTRACT**

The buoyancy of a marine seismic cable is controlled by transferring water into and out of individual buoyancy units located between sections of the cable. Each buoyancy unit includes a chamber containing a confined gas maintained at a pressure greater than ambient water pressure, a pump for introducing water into the chamber, and means for expelling water as necessary. A control system which permits both manual and automatic adjustments of the cable buoyancy is provided. This makes possible the towing of the cable at essentially constant depths behind an initial cable section fitted with a depth controller.

20 Claims, 16 Drawing Figures





LOGIC EQUATIONS

- $$\begin{aligned}
 1. \text{ VALVE}_n \text{ OPEN} &= (\overset{\uparrow}{\text{UP}}_n + \overset{\uparrow}{\text{FCPHI}}_n + \overset{\uparrow}{\text{SURFACE}}) \cdot (\text{VALVE}_n \text{ OPEN ENABLE}) \\
 2. \text{ VALVE}_n \text{ OPEN ENABLE} &= \overline{\text{DOWN}}_n \\
 3. \text{ VALVE}_n \text{ CLOSE} &= (\overset{\uparrow}{\text{UP}}_n + \overset{\uparrow}{\text{DOWN}}_n + \overset{\uparrow}{\text{FCPHI}}_n) \cdot (\text{VALVE}_n \text{ CLOSE ENABLE}) \\
 4. \text{ VALVE}_n \text{ CLOSE ENABLE} &= \overline{\text{SURFACE 2}} \\
 5. \text{ PUMP}_n \text{ RUN} &= (\text{FCPLO}_n + \text{DOWN}_n) \cdot (\text{PUMP}_n \text{ ENABLE}) \\
 6. \text{ PUMP}_n \text{ ENABLE} &= \overline{\text{UP}}_{n2} \cdot \overline{\text{SURFACE 2}}
 \end{aligned}$$
- FIG. 4**

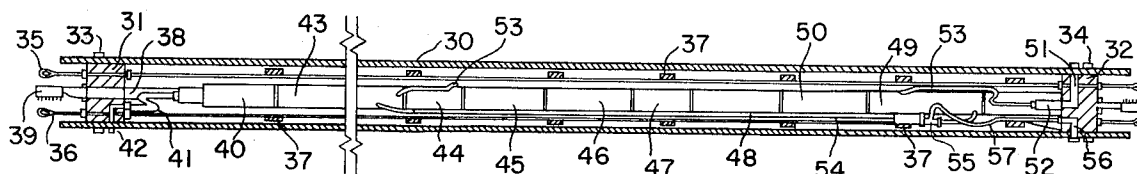


FIG. 3

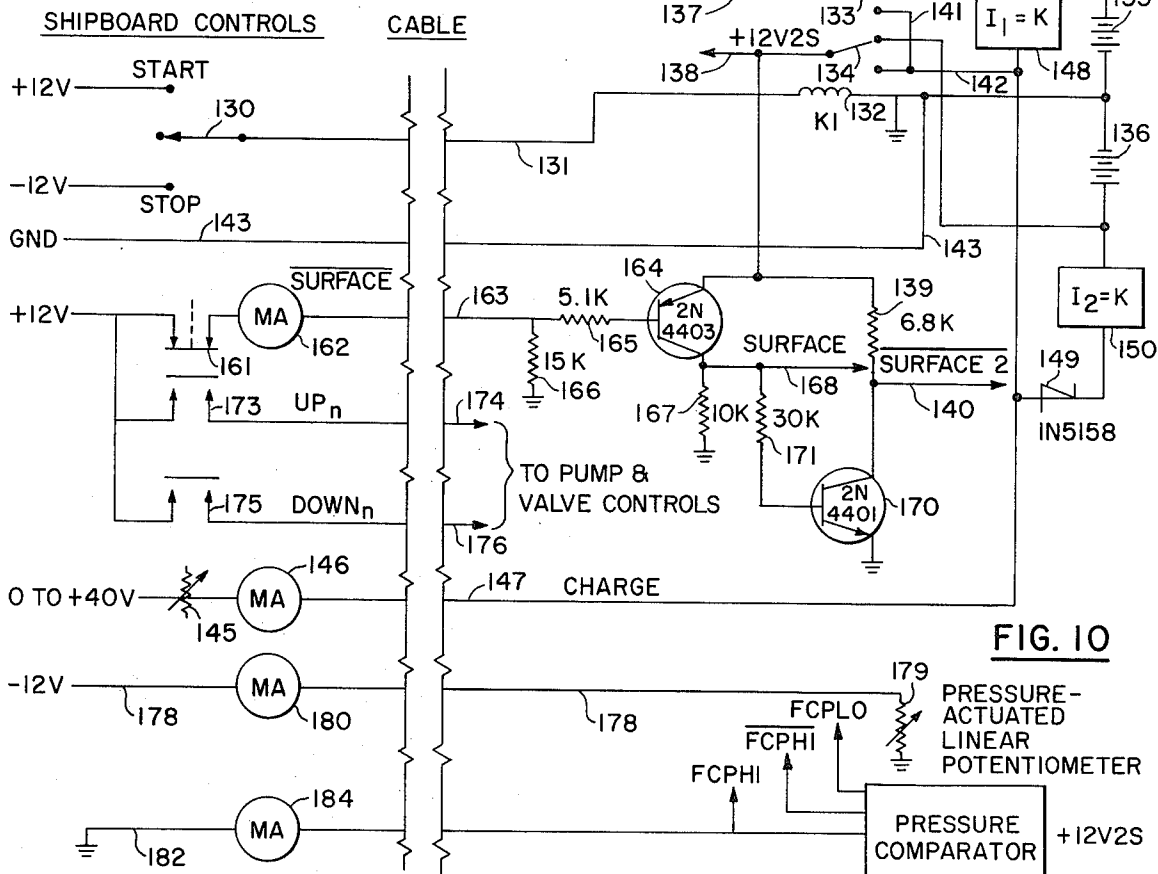


FIG. 10

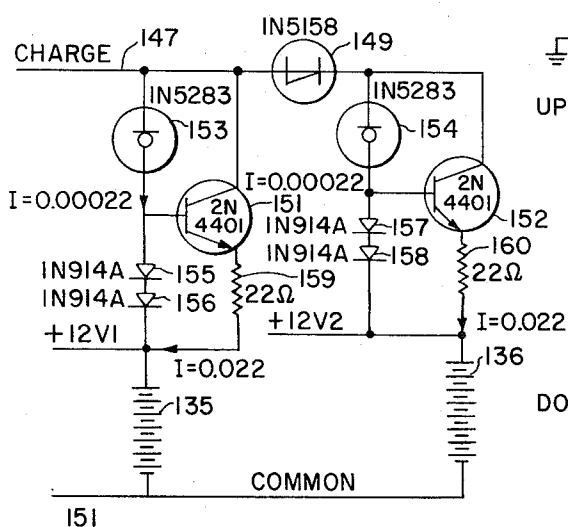
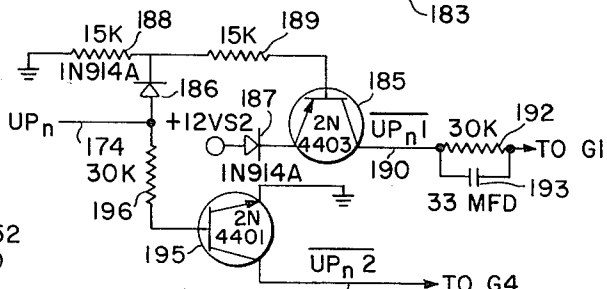
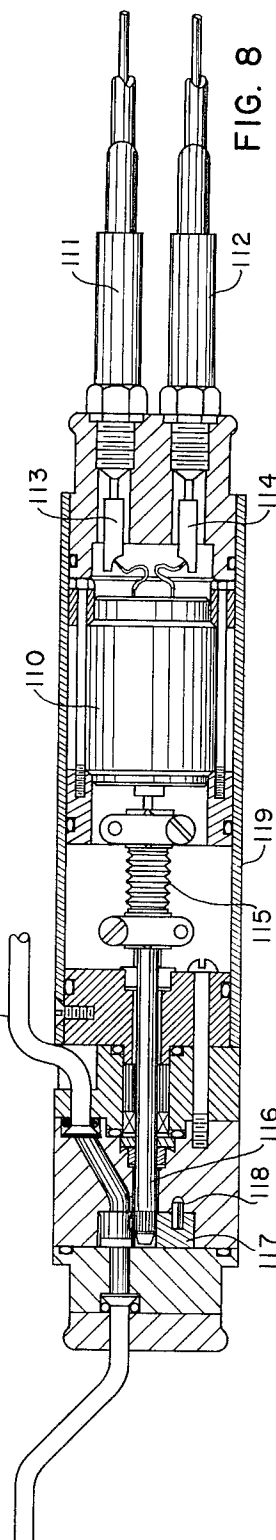
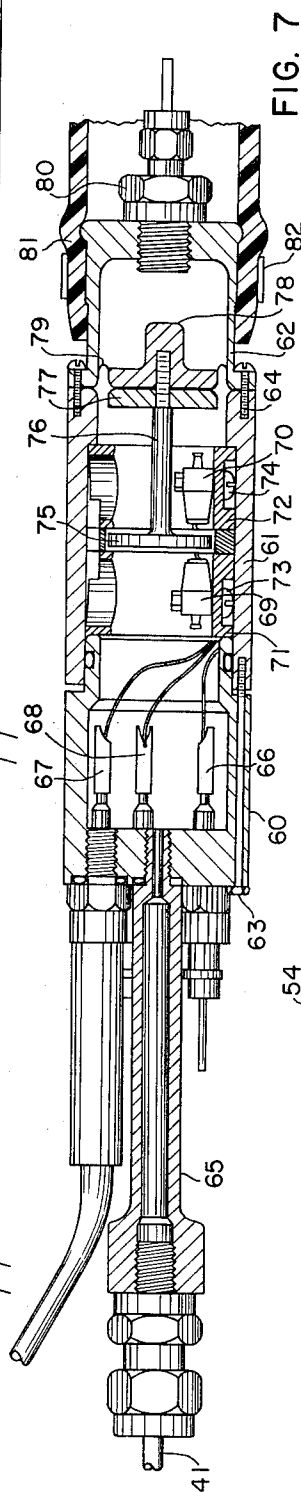
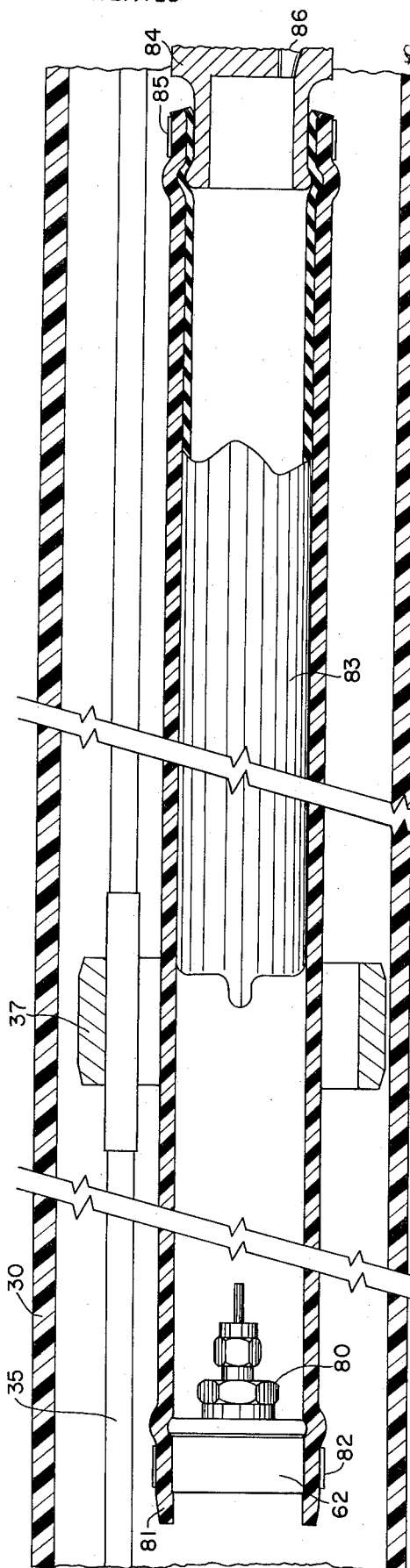


FIG. 11





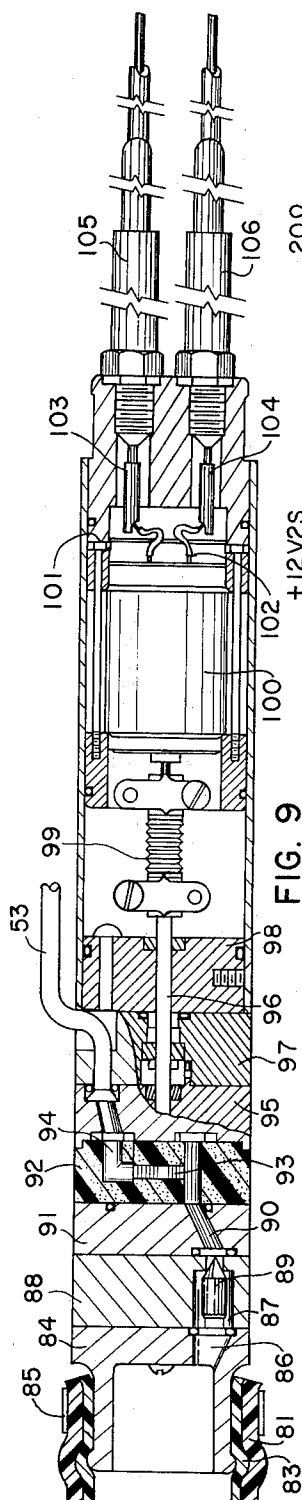


FIG. 9

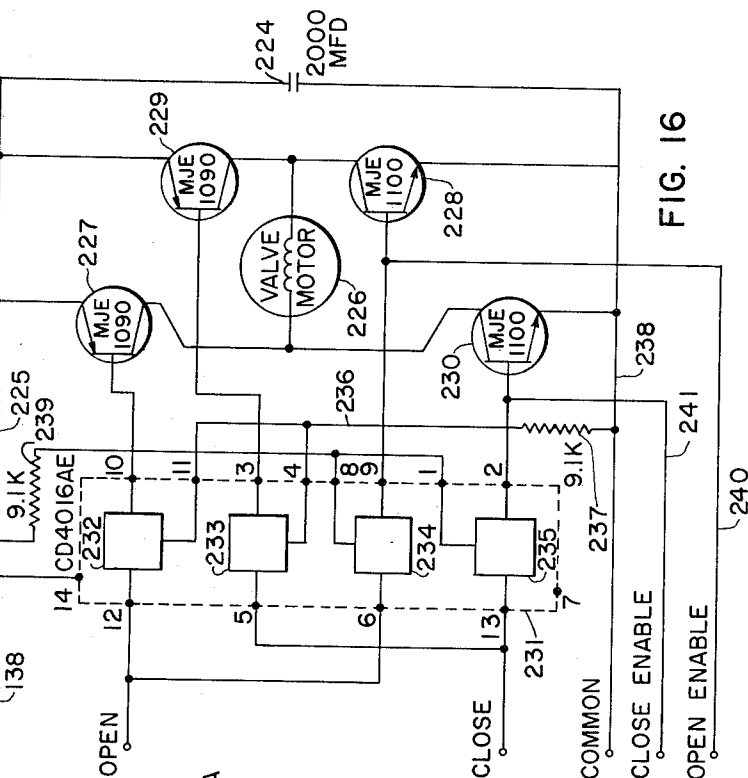


FIG. 16

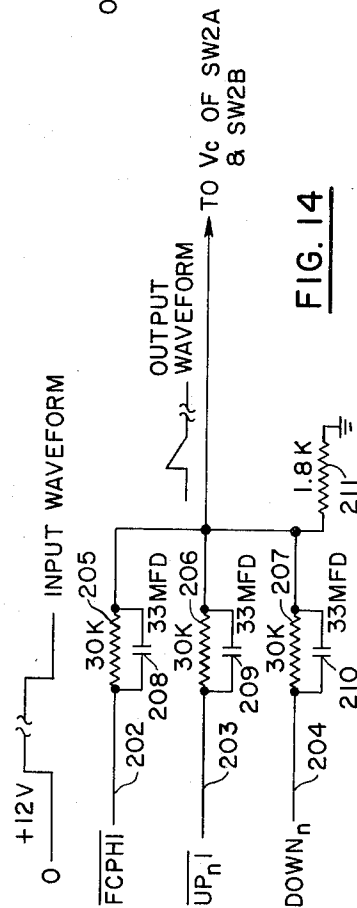


FIG. 14

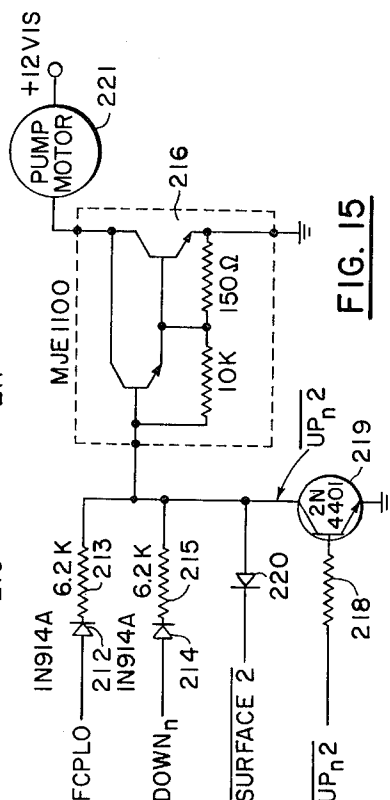


FIG. 15

MARINE SEISMIC CABLE BUOYANCY SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to seismic cables for use in marine prospecting operations and is particularly concerned with a method and apparatus for controlling the buoyancy of such cables.

2. Description of the Prior Art

Seismic prospecting operations carried out in marine areas generally require the use of a seismic cable or streamer containing hydrophones. This cable is normally made up of sections that can be joined to form an assembly of any desired length. Each section is usually a long tubular member having an outer wall of heavy plastic or similar material. A bulkhead at each end of the section provides a fluid-tight seal about electrical conductors and tension cables extending through the section. The hydrophones are spaced at intervals within each section and the interior is filled with a light oil or similar material to give a neutral or slightly positive buoyancy. Depth controllers provided with vanes that can be adjusted to change the vane angle are installed at intervals along the cable's length. By monitoring the hydrostatic pressure at various points along the cable and automatically or manually adjusting the depth controller vanes, the cable can be maintained at the required depth during prospecting operations.

Although systems of the type described above generally provide adequate depth control and have been widely used, experience has shown that they have certain drawbacks. The principal difficulty is that the use of external depth controllers attached to the cable at intervals along its length results in the generation of acoustic noise which is picked up by the hydrophones and recorded. This noise tends to mask the desired signal and may result in a significant loss in signal quality. Other difficulties include the necessity for removing the controllers from the cable to permit recharging of the batteries used to move the vanes, the susceptibility of the units to unwanted lateral displacement in cross currents, and numerous problems associated with the remote control of such devices. Where remote control is attempted, it is generally limited to a system which transmits the same commands to all units, thus precluding separate control of individual units and limiting the amount of control which can be exercised from the tow vessel. It has been suggested that these problems might be avoided by eliminating the external depth controllers and employing in their place cable sections whose buoyancy can be adjusted to control the cable depth. Others have proposed that an oil or similar buoyant fluid be pumped into the buoyant sections through a small flexible tube extending from the towing vessel when an increase in buoyancy is required and that excess buoyant fluid be discharged into the surrounding water when a reduction in buoyancy is needed. Although such a system might be practical under certain conditions, it has obvious disadvantages which have precluded its widespread use to date.

SUMMARY OF THE INVENTION

This invention provides an improved method and apparatus for controlling the buoyancy of a seismic cable or similar device which largely eliminates the difficulties associated with external depth controllers and other equipment available heretofore. The system of

the invention makes use of isolated buoyancy chambers located at intervals along the length of the cable. Each buoyancy chamber contains an expansible section within which a gas is maintained at a pressure in excess of the ambient water pressure. An electric pump associated with each buoyancy chamber permits the introduction of water into the chamber under sufficient pressure to further compress the confined gas. The reduction in the volume of gas in the chamber and the corresponding increase in the amount of water present results in a decrease in the buoyancy of the apparatus. When an increase in buoyancy is required, an electrically-actuated valve is opened and water is expelled from the buoyancy chamber as the gas expands. The buoyancy of the entire cable can thus be adjusted as necessary to maintain the required cable depth during a seismic prospecting operation. Since the system does not require external vanes or similar projections, the cable can be towed at relatively high speeds with little noise.

The buoyancy control system of the invention provides either manual or automatic control of the depth of individual sections of a marine seismic cable. Switches on a buoyancy control panel aboard the towing vessel are connected through cable conductors to each of the individual buoyancy control units in the cable or to each of several groups of units. These switches control operation of the motor and valve on each control unit so that the buoyancy can be increased or decreased at will. For automatic control, each of the buoyancy control units includes a pressure comparator which actuates the motor or valve in the unit in response to changes in pressure and thus serves to maintain the marine cable at constant buoyancy. This can be adjusted to operate at neutral buoyancy for any desired depth within the normal seismic cable operating range. Fail-safe features which will cause the cable to rise to the water's surface in the event of an emergency are also included in the system.

The method and apparatus of the invention have numerous advantages over seismic depth control systems advocated in the past. The use of streamlined control units of substantially the same diameter as the active sections of the streamer cable containing the hydrophones eliminates extraneous noise associated with paravanes and similar devices and makes possible higher towing rates than are ordinarily feasible with conventional systems. The vertical sensing devices required with paravanes and similar units are not required and hence no anomalous vertical force is needed at the point of control. The provision of both manual and automatic controls results in a versatile system which can be used under adverse conditions where conventional systems may not be applicable and which permits more precise control of cable depth than can normally be attained with conventional systems. The inclusion of fail-safe features which will cause the cable to rise to the surface in the event of a power failure or damage by a submerged object or another vessel reduces the risk of losing the cable and simplifies cable recovery operations in the event of an emergency. As a result of these and other advantages, the system of the invention makes possible substantial improvements in offshore seismic prospecting operations.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 in the drawing is a schematic representation

of a seismic prospecting operation carried out in accordance with the invention;

FIG. 2 is a block and flow diagram illustrating the major components of the buoyancy control system and their operation;

FIG. 3 is a longitudinal cross sectional view through a buoyancy control unit constructed in accordance with the invention;

FIG. 4 sets forth the logic equations involved in the system of the invention;

FIG. 5 is a logic diagram illustrating the pump and valve control system of the invention;

FIG. 6 is a longitudinal cross section through a buoyancy control unit of the invention showing the buoyancy chamber;

FIG. 7 illustrates, in longitudinal cross section, the pressure comparator employed in the apparatus;

FIG. 8 is a longitudinal cross section through the valve used in the system;

FIG. 9 is a longitudinal cross section through the pump employed in the system;

FIG. 10 is a simplified schematic diagram of the circuitry employed in the buoyancy control system;

FIG. 11 is a circuit diagram of the constant current battery charging circuit employed in the system;

FIGS. 12 and 13 are schematic diagrams of inverter circuits used in the system;

FIGS. 14 and 15 are schematic diagrams of logic gates employed in the system; and,

FIG. 16 is a schematic diagram showing details of the valve motor control and drive system of the buoyancy control apparatus of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the offshore seismic prospecting operation illustrated in FIG. 1 of the drawing, a marine seismic cable is shown being pulled behind a tow vessel 11 fitted with a reel 12 or the like for storing the cable aboard the vessel and unreeling it outwardly into the water. The cable shown includes an initial lead-in section 13 which extends between the towing vessel and the active portion of the cable, buoyancy control units 14 and 15, and detector section 16. The entire cable may range from a few hundred feet to 10,000 feet or more in length and will normally include a plurality of depth control units and detector sections. The number of each and their arrangement within the cables will depend in part upon the particular seismic prospecting operation to be carried out and the type of active cable sections employed. In general, however, the buoyancy control units should be located at intervals along the cable length sufficiently close together to permit maintaining of the cable at a substantially uniform depth. This depth will normally be between about 10 and about 50 feet below the water's surface, depending in part upon the particular type of seismic operation being conducted, sea conditions, the towing speed, and other factors.

The initial lead-in section 13 of the cable assembly shown in FIG. 1 may be fitted with a conventional paravane or similar depth controller 17 which will serve to hold the forward end of the cable at the desired depth beneath the surface of the water as it is towed. Such a device, if used, will normally be positioned well forward of the active section of the cable so that the noise generated will not seriously interfere with the signals

picked up by the hydrophones. In lieu of a paravane or similar device, a weighted lead-in section into which fluid can be introduced from the tow vessel to permit adjustment of the depth at which the lead-in section moves through the water may be employed. With either type of lead-in section, the apparatus of the invention functions to maintain the rest of the cable at an average neutral buoyancy so that it will readily trail at constant depth behind the lead-in section.

The block and flow diagram of FIG. 2 in the drawing illustrates the major components of the system of the invention and the overall mode of operation of the system. As can be seen from FIG. 2, the system includes a buoyancy chamber 20 with which a pressure comparator 21 and a calibration pressure chamber 22 are associated. Bypass valve 23 and pump 24 permit the transfer of water between the buoyancy chamber and the surrounding body of water 25 along separate paths. A valve and pump control means 26 regulates operation of the pump to introduce water into the buoyancy chamber in response to input signals from either the tow vessel or the pressure comparator. Operation of the bypass valve to permit the expulsion of water from the buoyancy chamber into the surrounding body of water is similarly regulated by the valve and pump control means in response to other signals from either the tow vessel or the pressure comparator. The buoyancy of the system is thus regulated by forcing water into or out of the buoyancy chamber upon receipt of signals which may be initiated manually aboard the tow vessel or generated automatically by the pressure comparator.

The general arrangement of the apparatus of the invention is shown in FIG. 3 of the drawing. The outer housing of the apparatus will normally comprise an elongated cylindrical tube or sleeve 30 of polyvinyl chloride, polypropylene, or similar material. The material selected should be flexible, impervious to fluids, and resistant to deterioration in the presence of water, brine, ultraviolet light, and oil. Laminated materials reinforced with fiberglass or the like may be employed if desired. Bulkheads 31 and 32 are located near the ends of the housing and are held in place by bands or straps 33 and 34. Cables 35 and 36 of steel or similar material extend through the apparatus and serve to take the tension during towing operations. Although only two cables are shown in FIG. 3, the apparatus will normally include three cables spaced at 120° intervals. The bulkheads are sealed about the cables to prevent the leakage of fluids into or out of the apparatus. Spacer rings 37 are mounted between the cables and the inner wall of the housing to hold the assembly in shape.

An electrical cable 38 extends through the housing from an electrical connector 39 on one end of the apparatus to a similar connector on the other end. The connectors are designed to mate with similar connectors on adjacent sections of the seismic cable so that charging current and control signals from the apparatus aboard the tow vessel can be transmitted to the various buoyancy control units spaced along the cable and seismic signals can be transmitted from the hydrophones to the seismic recording apparatus on the tow vessel. The bulkheads are sealed around electrical cable 38 to prevent fluid leakage. The housing can be connected to adjacent sections of a seismic cable by making up the electrical connectors, connecting the tension cables extending from the bulkheads to similar cables in the ad-

jacent sections, positioning the ends of sleeve 30 over the bulkheads on the adjacent sections, and then fastening the sleeves in place with straps or bands.

The buoyancy control unit components mounted within the housing 30 in FIG. 3 include a pressure comparator 40 which is connected by tubing 41 to an air injection port 42 in the side of bulkhead 31. The pressure comparator includes a calibration pressure chamber which is not shown in FIG. 3. The air injection port is provided with a fluid-tight cap and may be fitted with a check valve to facilitate the introduction of air or gas into the chamber under pressure. The buoyancy chamber 43 is located adjacent the pressure comparator and next to this is positioned an electrical pump 44. The batteries used to power the pump are contained in area 45. Area 46 contains a part of the electronic equipment used to control operation of the apparatus. A depth and pressure sensor 47, which may be of conventional design, is located adjacent the electronic components. Additional electronic components are located in area 48 and the batteries used to power the bypass valve 49 are located in area 50. Water intake port 51 is located in the side of bulkhead 32 and communicates with water intake line filter 52. Water line 53 extends from the filter to the intake port on pump 43. Water discharge line 54 extends from the buoyancy chamber to the bypass valve through T 55. The discharged water passes from the bypass valve through filter 52, backwashing off any solids accumulated during the intake step, and is ejected through port 51. Port 56 and branch line 57 permit the initial injection of water into the system without running the pump. The individual components thus employed in the system are described in greater detail below.

The pressure comparator employed in the apparatus described above is shown in detail in FIG. 7 of the drawing. This unit includes a cylindrical housing which is preferably made up of an inlet section 60, an intermediate section 61, and a connecting section 62 in order to facilitate assembly of the apparatus and permit ready access to the internal components. The three sections are held together by bolts 63 and 64 as shown. Inlet section 60 is provided with a fitting 65 by means of which air line 41 is connected to the comparator. Electrical leads extend through fluid-tight fittings in the end wall of the inlet section to terminals 66, 67 and 68. Leads extend from these terminals to snap-action switches 69 and 70, which are mounted within intermediate section 61 and held in place by cylindrical spacers 71 and 72 and by bolts 73 and 74. Piston 75 is positioned between the two switches so that the switches are actuated by movement of the piston. Each switch has two positions, an "on" position and an "off" position. The "off" position of switch 70 is not used. Rod 76 extends from piston 75 to members 77 and 78, between which rolling diaphragm 79 is positioned. The outer edge of the diaphragm is held in place between the ends of intermediate section 61 and connecting section 62. Fittings 80 in the end of the connecting section permit the passage of air between the pressure comparator and the adjoining buoyancy chamber. The outer housing 81 of the buoyancy chamber extends over the outside of the connecting section 62 and is held in place by band or strap 82.

The buoyancy or flotation chamber of the apparatus is shown in FIG. 6, which also depicts outer housing 30, tension member 35, and supporting ring 37. The outer

wall of the flotation chamber is an elongated, flexible tube 81 of heavy plastic material which will bend readily but tends to maintain a circular cross-section of fixed diameter. One end of this member extends over the connecting end 62 of the pressure comparator as indicated in FIG. 7 and the other end is mounted on the end of the pump assembly as shown in FIG. 9. Positioned within the flotation chamber is an elongated collapsible bladder 83 of thin rubber, plastic or similar highly flexible material. One end of this bladder extends over the end of the pump assembly to permit the movement of water into and out of the bladder. The other end is sealed to preclude escape of the water as shown in FIG. 6. In lieu of such a bladder, a low friction piston or other device for separating the air and water in the flotation chamber may in some cases be employed.

The dimensions of the flotation chamber and bladder will depend in part upon the size and weight of the marine seismic cable or other device with which the buoyancy controllers are to be used, the spacing of the controllers within the cable assembly, and other factors. In general, the buoyancy controller is normally designed with a flotation chamber volume such that the average density of the controller unit and the associated length of active marine cable equals the average density of sea water when the chamber is two-thirds full of water. Since the dimensions and densities of all the materials which are used in the active cable section and the buoyancy controller unit are known, the required volume for a particular case can be readily calculated. In a typical case, the float chamber may have an inside diameter of about 1 inch and may be 24 feet or more in length. A 24 foot chamber of this size would have a capacity of about 1 gallon and would result in a weight increase of approximately 6 pounds when two-thirds filled with sea water. If a chamber of this type is located between each two active sections of a typical marine seismic cable, a length considerably less than 24 feet would normally be adequate.

The air or gas pressure employed in the pressure comparator and flotation chamber will depend primarily upon the depth at which the marine seismic cable or similar device is intended to operate. Marine seismic cables are normally operated at depths between about 30 and about 40 feet but in most cases the buoyancy controller will be designed to function at all depths from zero to about 50 feet or more. The air or gas pressure in the pressure comparator and buoyancy chamber should be sufficiently in excess of the hydrostatic pressure to rapidly expel water from the bladder when the bypass valve in the apparatus is opened. The ambient pressure in the zero to 50 foot depth range varies from atmospheric up to about 37 pounds per square inch absolute. The air or gas pressure in the comparator section 60 will therefore normally be set at about 45 pounds per square inch absolute. That in the flotation chamber will normally be the same when the chamber is two-thirds full of water. This is a practical working pressure for the materials used in the buoyancy control unit and one which can be employed without any safety hazard. Higher pressures can be used if desired, however.

The pump assembly employed in the apparatus of the invention is shown in FIG. 9 of the drawing. This assembly includes a discharge tube 84 over the end of which buoyancy chamber 81 and bladder 83 are

held in place by strap or band 85. A discharge port 86 extends through the wall of the discharge section and communicates with passageway 87 in adjacent member 88 containing a check valve 89. This check valve prevents the flow of water from the flotation chamber back through the pump assembly. Passageway 90 extends from the check valve through adjacent section 91 into section 92, where drive gear 93 and an associated idler gear which does not appear in the drawing serve as the pumping elements. Passageway 94 extends from the gears into adjacent section 95 where it communicates with water intake line 53. The drive gear 93 is mounted on pump shaft 96, which is supported by suitable bearings and seals in sections 97 and 98 of the pump assembly. The end of shaft 96 is connected by drive coupling 99 to the shaft of a fractional horsepower direct current electric motor 100. The motor is powered through leads 101 and 102, which are connected to contacts 103 and 104. Power is supplied to the contacts through fluid-tight fittings 105 and 106. It will be understood, of course, that the invention is not restricted to the particular type of pump assembly shown in the drawing and that other electrically powered pumps may be used.

FIG. 8 in the drawing is an enlarged view of the electrically driven bypass valve assembly employed in the apparatus of FIG. 3. The bypass valve assembly includes a fractional horsepower direct current electrical motor 110 which is powered by leads extending through fluid-tight fittings 111 and 112 to terminals 113 and 114. The motor shaft is connected through drive coupling 115 to rod 116 on which valve plate 117 is mounted. The valve plate contains a slot extending through a 90° arc into which pin 118 extends and an opening through which water may pass when the plate is in the open position. The slot and opening do not appear in the drawing. The valve mechanism is enclosed in an elongated fluid-tight housing 119 which is made up in sections to facilitate assembly of the apparatus and ready access to the components. Water discharge line 54 enters the housing through suitable fluid-tight connections on each side of the valve plate so that the flow of water through the line can be controlled by means of the valve. Again it will be understood that the invention is not restricted to the particular apparatus shown in the drawing. In lieu of the motor driven valve depicted in FIG. 8, a valve actuated by a solenoid or similar device may be employed if desired.

The operation of the components described above and the control system employed can best be understood by referring to FIGS. 4 and 5 of the drawing. FIG. 4 sets forth the logic equations applicable to the system. The arrows in the equations indicate that the leading edge of the signal satisfies the specified condition. Where no arrow is shown, the condition is stable. FIG. 5 is a simplified logic diagram illustrating the control system and the interrelationships between the various components. Referring to FIG. 5, which represents a single buoyancy control unit, it will be noted that three manual control signals from a buoyancy control panel aboard the tow vessel are indicated. Two of these control signals, UP_n and $DOWN_n$, are specific to the individual buoyancy control unit. The third manual signal, SURFACE, is a generalized signal applied to all of the buoyancy control units in the marine cable assembly. In addition, START and STOP signals activate and deactivate all of the units in the assembly. These signals

permit manual control of the operation of the system from aboard the tow vessel.

As indicated earlier, the apparatus of the invention permits control of the buoyancy of a marine seismic cable or similar device by pumping water into one or more buoyancy or flotation chambers located at intervals along the length of the cable assembly when a decrease in buoyancy is needed and by expelling water from the chambers through the bypass valves when an increase in buoyancy is required. Manual operation of the pump and valve are controlled by the UP_n , $DOWN_n$ and SURFACE signals from the shipboard controller. The SURFACE signal is maintained as long as the electrical conductor between the buoyancy control unit and the shipboard controller is unbroken. If this circuit is interrupted by the activation of a switch on the shipboard controller or by a break in the cable between the tow vessel and the buoyancy control unit, inverter I_1 in FIG. 5 generates a SURFACE signal which is transmitted to inverter I_4 and OR gate G2 in FIG. 5. The circuitry of the various gates, inverters and switching components shown in FIG. 5 is shown elsewhere and will be described later. Provided that the system is in the VALVE OPEN ENABLE state, the SURFACE signal from inverter I_1 through OR gate G2 actuates switching circuitry SW1A and SW1B to energize the valve motor and open the valve. Air pressure within the flotation chamber thereupon displaces water from the bladder within the chamber, increasing the buoyancy of the buoyancy control unit and causing the seismic cable assembly to rise to the surface. This is a fail-safe feature which minimizes the risk of loss of the cable and facilitates its recovery in the event of an emergency.

As indicated by logic equation number 2, the VALVE OPEN ENABLE state depends on the absence of a $DOWN_n$ signal. The $DOWN_n$ signal is generated by inverter I_3 and transmitted to switching assembly SW1B. The initiation of a $DOWN_n$ signal aboard the tow vessel results in a short pulse to OR gate G1 and discontinuance of the $DOWN_n$ signal from inverter I_3 . Provided that the system is in the VALVE CLOSE ENABLE state, the $DOWN_n$ signal results in closing of the valve as indicated in logic equation number 3. Equation 4 shows that the VALVE CLOSE ENABLE state depends upon the absence of a SURFACE signal. Current from inverter I_4 flows to switching unit SW2B in the absence of such a SURFACE signal so that the valve motor can be actuated in response to the CLOSE signal from OR gate G1 and the valve can be closed.

The presence of the $DOWN_n$ signal from the tow vessel also produces current from OR gate G3 and, provided the system is in the PUMP ENABLE state, produces a signal from NAND gate G4 which actuates the pump motor to pump water into the bladder within the flotation chamber. This is indicated by logic equation number 5. The PUMP ENABLE state requires the absence of an UP_n and SURFACE signal as shown by equation 6. Currents representing the $SURFACE_n$ and UP_n conditions flow from inverters I_4 and I_5 , respectively, as long as the system is not in a SURFACE or UP condition.

The initiation of an UP_n signal aboard the tow vessel causes current to flow through OR gate G2 and, if the system is in the VALVE OPEN ENABLE state, results in actuation of valve motor switching assemblies SW1A and SW1B to energize the motor and open the valve.

This also discontinues the UP_n current so that the system is no longer in the $PUMP_n$ ENABLE state. It can thus be seen that manual control of the apparatus by means of the SURFACE, UP_n , and $DOWN_n$ controls aboard the tow vessel permits the taking on and expulsion of ballast water from each of the buoyancy control units in the marine seismic cable assembly. By monitoring the cable depth as indicated by the shipboard readings from the hydrostatic pressure sensors in the buoyancy control units and adjusting the buoyancy as necessary, the depth of the cable assembly or any part of the assembly below the water's surface can be controlled at will.

The pressure comparator in each buoyancy controller unit provides automatic control of buoyancy if desired. As indicated earlier, the gas pressure in the calibration pressure chamber is normally adjusted so that the unit and associated section of the seismic cable will have neutral buoyancy when the bladder in the flotation chamber is about two-thirds full of water. This pressure will generally be on the order of 30 pounds per square inch gauge. With experience, the pressure can be calibrated quite accurately, particularly if care is taken to employ air at ambient sea water temperature. The diaphragm in the pressure comparator is exposed to the calibration pressure on one side and the flotation chamber pressure on the other. A differential pressure of less than 1 pound per square inch will drive the diaphragm from one limit stop to the other stop. With these two pressures equal, the diaphragm will reside between the limit stops. As indicated in FIG. 5, the pressure comparator generates three signals. When the diaphragm is at its limit stop near the flotation chamber, one of the switches in the unit is actuated to provide an active output which is called "Flotation Chamber Pressure Low," abbreviated FCPLO. With the diaphragm at the opposite limit stop, the other switch yields an active output which is called "Flotation Chamber Pressure High," abbreviated FCPHI. When the diaphragm is balanced between the two limit stops, both switches are unactuated and their normally closed contacts yield the respective complementary signals $\overline{FCPLO}$ and $\overline{FCPHI}$. The FCPHI signal is not used in this particular embodiment of the apparatus.

Automatic control is initiated by turning off the Up, DOWN, and SURFACE shipboard controls. As indicated by equation 2 in FIG. 4, the valve control system will then be in the VALVE_n OPEN ENABLE state. The SURFACE₂ condition will exist, placing the system in the $PUMP_n$ ENABLE state and the VALVE CLOSE ENABLE state. The initiation of a FCPHI_n signal at the pressure comparator, due to movement of the diaphragm away from the flotation chamber, will actuate the valve motor as shown by equation number 1 and cause the valve to open so that ballast water will be discharged from the flotation chamber and the buoyancy of the system will increase. As indicated by equation number 3, the valve will close when the diaphragm reaches the intermediate position and the pressure comparator emits a $\overline{FCPHI}_n$ signal. If, on the other hand, the air pressure in the flotation chamber decreases and the diaphragm moves toward the flotation chamber, a FCPLO signal will be initiated. As indicated in equation number 5, this will start the pump and result in the addition of water to the bladder in the flotation chamber. The added water produces a reduction

in the buoyancy of the buoyancy controller unit and associated portion of the seismic cable.

FIG. 10 in the drawing is a simplified schematic diagram showing the electrical circuitry of the buoyancy controller unit. The shipboard controls shown in FIG. 10 include a start-stop switch 130 which is normally open and may be momentarily moved into either the START or STOP position. The START contact is connected to the positive side of a 12 volt direct current power source aboard the tow vessel. The STOP contact is connected to a negative 12 volt source. Lead 131 in the seismic cable connects the switch to a magnetic latching relay 132 in each of the buoyancy units. The coils of these relays are connected in parallel so that all of the buoyancy units are energized simultaneously and each relay operates independently of the others. Energizing of the latching relay by the momentary movement of switch 130 into the START position moves the relay contacts 133 and 134 into the position shown in FIG. 10 so that battery banks 135 and 136 are connected to their loads through leads 137 and 138. The momentary movement of switch 130 into the STOP position reverses the polarity of the coil in magnetic latching relay 132 and moves contacts 133 and 134 from the position shown in FIG. 10 into their alternate position. In this latter position, the batteries are disconnected from the load circuits in the buoyancy control unit. Power through leads 137 and 138 is obtained from the tow vessel through the charging circuit to which leads 141 and 142 are connected. This permits continued operation of the system in the event of battery failure.

The battery charging circuitry of the apparatus is shown schematically in FIG. 10 and depicted in greater detail in FIG. 11. As indicated in FIG. 10, the charging current is provided by a zero to 40 volt direct current source aboard the towing vessel and is monitored and controlled by potentiometer 145 and meter 146. Lead 147 extends through the cable and is connected to battery bank 135 through charging circuit 148 and to battery bank 136 through diode 149 and charging circuit 150. The negative sides of the batteries are connected to ground through lead 143. As shown in FIG. 11, the charging circuits comprise NPN transistors 151 and 152 which are controlled by current from constant current diodes 153 and 154, connected in series with diodes 155 and 156 and diodes 157 and 158 respectively. Current passed by the transistors flows through resistors 159 and 160 to batteries 135 and 136. In the particular circuit shown in FIG. 11, battery bank 135 will charge at 22 milliamps as long as the voltage on charge line 147 is equal to or greater than 15 volts. Four layer diode 149 prevents a charge to battery bank 136 until the voltage on charge line 147 is raised to 25 volts. This bank then continues to charge at 22 milliamps until the charge line voltage is reduced below 15 volts. This permits the maintenance of a trickle charge on the battery banks and insures long battery life. Each bank will preferably consist of one or more nickel cadmium batteries.

The SURFACE, UP_n , and $DOWN_n$ shipboard controls are powered from a 12 volt direct current source aboard the tow vessel. The surface control system includes normally closed switch 161 and meter 162. Under normal operating conditions, current flows from the 12 volt supply through the switch, meter, and lead 163 and through resistor 166 to ground. The top end

of resistor 166 is maintained at plus 12 volts. This keeps transistor 164 cut off so that the SURFACE signal remains at zero volts. NPN transistor 170 is also cut off and hence the SURFACE2 signal will be at plus 12 volts. Transistor 164 and resistors 165, 166, and 167 form the inverter I_1 of FIG. 5. Transistor 170 and associated resistors 167, 171, and 139 constitute the inverter I_4 of FIG. 5. It should be pointed out that the signal SURFACE, although appearing at the top of resistor 166, arises at the plus 12 volt shipboard supply. The SURFACE and SURFACE2 signals have their source in the 12 volt battery 136 which is in the buoyancy controller unit out in the water. They are normally controlled by the presence or absence of the SURFACE signal but do not depend upon the shipboard supply for power. Thus, if the cable breaks or if conductor 163 becomes grounded due to accident, PNP transistor 164 will turn on. This causes SURFACE to rise to plus 12 volts. A positive pulse is thereupon delivered to OR gate G2 and serves to open the bypass valve. While the SURFACE signal remains at plus 12 volts, base current to NPN transistor 170 will flow through resistor 171, and the SURFACE2 signal will remain at zero. This action disables the pump motor at NAND gate G4. Surfacing action can also be controlled manually, of course, by actuating the normally closed switch 161. Under normal conditions, while switch 161 is closed, the milliammeter 162 will indicate about 0.8 ma per unit. Abnormal cable conditions can thus be observed on this meter.

The 12 volt DC current which provides the UP_n signal from the shipboard control system passes through normally open switch 173 and over lead 174 to OR gate G2 in the valve motor control system and to inverters I_2 and I_5 to produce the UP_n1 and UP_n2 signals. A current representing the $DOWN_n$ signal passes through normally open switch 175 and over lead 176 to OR gate G1, OR gate G3, and inverter I_3 in the pump and valve motor control systems. Lead 178 is connected to the negative side of a 12 volt direct current source aboard the tow vessel and passes through the cable to a pressure actuated linear potentiometer 179 which serves to indicate the hydrostatic pressure on the buoyancy control unit and thus provide a measure of the depth of the unit. Meter 180 on the shipboard control panel provides a depth indication which can be used in manual operation of the apparatus. As indicated earlier, any of a variety of commercially available pressure sensors may be employed. The system will preferably include a pressure sensor and shipboard indicator for each buoyancy control unit in the marine seismic cable assembly but in some instances the pressure sensors may be omitted from certain of the buoyancy control units. Conductor 182 from the pressure comparator 183 extends through the cable to a meter 184 on the tow vessel to provide a shipboard indication of the FCPHI signal from the comparator.

FIG. 12 in the drawing is a detailed schematic of inverters I_2 and I_5 , which process the UP_n signal in the control system. Inverter I_5 is comprised of NPN transistor 195 and associated resistor 196. When the UP_n signal becomes positive due to closure of the normally open switch 173, forward bias current is introduced to transistor 195, pulling the UP_n2 line to ground potential due to the conduction of transistor 195. This will inhibit the pump motor through the action of NAND gate G4. At the same time, the UP_n signal is applied to OR

OR gate G2 through a pulse forming network consisting of a resistor and a capacitor. Gate G2 is schematically identical to gate G1, shown in FIG. 14. The resulting output pulse from gate G2 causes the valve motor to open the bypass valve. At the same time, the UP_n1 line is disconnected from the plus 12 volts source and capacitor 193 then discharges through resistor 192. This disconnecting action is caused by inverter I_2 , comprising PNP transistor 185, resistors 188 and 189, and diodes 186 and 187. Before application of the positive UP_n signal, transistor 185 was conducting due to base current flowing to ground through diode 187, the base-emitter junction of 185, resistor 189 and resistor 188. When UP_n is at plus 12 volts, no base current can flow because the cathode of diode 186 will also rise to approximately plus 12 volts. When the operator on the tow vessel releases the UP_n switch, current through diode 186 ceases, and forward biasing of transistor 185 again occurs. The renewed conduction of transistor 185 causes the sudden charging of capacitor 193 which delivers a pulse to OR gate G1. The resulting output pulse from G1 causes the valve motor to close the valve.

FIG. 13 of the drawing depicts details of inverter I_3 , which is used to inhibit the opening of the bypass valve in the presence of a positive $DOWN_n$ signal. This circuit includes NPN transistor 197, associated resistors 198 and 199, the diode 200. In the absence of a positive $DOWN_n$ signal, transistor 197 has no source of base current and is therefore cut off. The $DOWN_n$ signal is held at plus 12 volts by resistor 199, thus preventing the conduction of diode 200 and enabling the action of the VALVE OPEN circuitry. However, if switch 175 should be closed, a source of base current is provided for transistor 197. This base current flows to ground through resistor 198, and the base-emitter junction. Transistor 197 now becomes conducting. The $DOWN_n$ line is clamped to ground by this conducting action and the VALVE OPEN circuitry cannot function because it too is held at near ground potential by diode 200.

FIG. 14 in the drawing illustrates OR gate G1 in the control system. As indicated in FIG. 5, this gate provides the VALVE CLOSE signal for the valve motor control system. The input signals to the OR gate consist of the FCPHI signal from the pressure comparator, the UP_n1 signal from inverter I_2 and the $DOWN_n$ signal from the shipboard control panel. These signals are admitted by means of leads 202, 203 and 204 as rectangular input waveforms and are shaped by means of resistors 205, 206 and 207 and associated parallel condensers 208, 209 and 210. The output waveform is a signal which first rises and then decreases exponentially, thereafter remaining at a low level for the duration of the input signal. This positive pulse, connected to ground through resistor 211, is applied to the valve motor control circuitry as the VALVE CLOSE signal. OR gate G2 is schematically identical to gate G1. Both gates, in the apparatus shown, turn on their respective switches for about 80 milliseconds in response to a positive-going voltage step at any one of the three input terminals. This 80 millisecond time period is sufficient to allow the valve motor to drive the valve from one limit stop to the other. Two or more successive inputs steps to the same gates cause no change in the valve position. It will be understood, of course, that the particular components shown have been selected for use with a motor which will make the necessary one-fourth rev-

olution in response to an 80 millisecond signal and that other motors will require different components.

FIG. 15 in the drawing shows details of OR gate G3 and NAND gate G4 in the pump motor control system. The OR gate includes diode 212 and resistor 213 through which the input FCPLO signal from the pressure comparator is applied and diode 214 and resistor 215 through which the DOWN_n signal from the shipboard control panel is applied. Either of these signals will result in the application of a positive voltage to Darlington transistor 216 if the system is in the PUMP ENABLE state. The application of an UP_n2 voltage through resistor 218 to NPN transistor 219 turns on the transistor, clamping the base of transistor 216 to ground. When SURFACE 2 is at zero volts, it clamps the base of transistor 216 to ground through diode 220. Either of these conditions causes the pump to be disabled. Transistor 216 connects pump 221 to ground in the presence of a signal from the OR gate so that power from the 12 volt input to the pump causes the pump to operate. This operation will continue as long as the signal from the OR gate persists.

The valve motor control system in the apparatus is shown in FIG. 16 of the drawing. Energy from a bank of 12 volt batteries is stored on the 2,000 MFD capacitor 224 through lead 138 and resistor 225. This energy is available to run the valve motor 226 in either direction through the selective conduction of transistors 227 and 228 or 229 and 230. The operation of these transistors is controlled by integrated circuit 231, which consists in essence of four independently actuated switches, 232, 233, 234 and 235. These switches are normally open, and all four of the transistors are therefore open, resulting in no valve motor action.

The application of an OPEN signal from OR gate G2 to terminals 6 and 12 of the integrated circuit causes the closure of switches 232 and 234. This results in the conduction of transistor 227 due to the flow of base current through its emitter-base junction to terminal 10 and out on terminal 11 of switch 232, thence through lead 236 and resistor 237 to ground 238. Transistor 228 will also conduct, because of base current flowing from plus 12 volts through resistor 239 to terminal 8 of switch 234, out on terminal 9 and to ground 238 through the base-emitter junction of transistor 228. Although the OPEN signal persists for only 80 milliseconds, this is long enough for the valve motor to open the valve, utilizing energy from capacitor 224. This action cannot occur, however, if the OPEN ENABLE line 240 is at ground potential, because the base of transistor 228 must rise to about plus one volt before 228 will conduct.

In a similar fashion, the application of a positive CLOSE signal from OR gate G1 to terminals 5 and 13 of the integrated circuit closes switches 233 and 235 and renders transistors 229 and 230 conducting if the CLOSE ENABLE line 241 is not at zero volts. This permits the flow of current from capacitor 224 through transistor 229, valve motor 226, and transistor 230 so that the valve motor operates in the opposite direction and closes the valve. Although the valve motor and control system shown in FIG. 16 are preferred for purposes of the invention, it will be understood that the apparatus is not restricted to this particular valve and control system, and that solenoids or other circuitry may be employed in lieu of that shown if desired.

In operating the buoyancy control unit, it is normally desirable that the entire seismic cable assembly follow the lead section containing the depth controller or similar device at the same depth. The operator on the tow vessel, by watching the pressure indicator gauges, can monitor the cable depth. If he observes that a particular section of the cable is running too shallow, he can actuate the DOWN switch for that particular section on the shipboard control panel. This sends an impulse through logic gate G1 to insure that the bypass valve is closed and at the same time disables the VALVE OPEN circuitry. The DOWN signal is a direct current voltage level and as such goes through OR gate G3 and NAND gate G4 causing the pump motor to run. This motor is controlled for unidirectional operation only and when running serves to pump ballast water into the float chamber, thereby reducing the buoyancy of this section of the seismic cable system and causing it to move down to a deeper level. When the pressure indicator on the panel shows that the cable section in question has reached the proper level, the operator may return the DOWN switch to its off position, thus stopping the pump so that no further change in the ballast condition of the flotation chamber occurs.

If the operator wishes to trim a particular cable section so that it will run at a shallower depth, he simply actuates the appropriate UP switch on the shipboard panel. This directs an impulse to gate G2, causing the bypass valve to open. The air or gas in the flotation chamber, under higher pressure than the ambient sea pressure, begins forcing ballast water from the chamber through the open bypass valve. At the same time, inverter I₅ disables NAND gate G4 to prevent the pump motor from running in response to any signal through OR gate G3. When the desired value is obtained on the pressure indicator on the shipboard panel, he may return the UP switch to its off position. This causes inverter I₅ to deliver a positive pulse to OR gate G1, which closes the bypass valve and stabilizes the system.

As pointed out earlier, the automatic control system operates when both the UP and DOWN shipboard controls are off. The operator can maintain manual control at all times, however, by placing both the UP and DOWN switches in their "on" positions. If this is done, the bypass valve is closed and both gates G2 and G4 are inhibited. This keeps the ballast conditions unchanged pending further manual signals by the operator. If a sufficient number of pressure indicators and control conductors are available, manual operation of the system is normally preferred because the operating depth of the cable can be trimmed whenever necessary to compensate for changing water or bottom conditions, errors in the automatic controls, or emergency conditions. In an emergency, the seismic cable system can be quickly converted to its most buoyant condition by actuation of the SURFACE switch. This removes the positive SURFACE signal from all controller units in the cable assembly simultaneously. It directs an impulse to OR gate G2 to open the bypass valve and allow compressed air or gas in the flotation chamber to begin the discharge of ballast water. It also prevents the pump motor from running.

When the system of the invention is under automatic control, the seismic cable assembly will normally glide smoothly through the water at the same depth as the lead section containing the paravane or depth control-

ler. All diaphragms in the pressure comparators will be in their neutral positions. Lateral water currents will have little effect upon the cable because of its streamlined shape. Under such conditions, no error signals will be generated by the pressure comparators. The bypass valves will remain closed and the pump motors will be idle. In the event that a small leak develops in a pump flow line or bypass line in one of the units, ballast water will slowly leak from the system, causing a reduction in flotation chamber pressure. This allows the air or gas in the flotation chamber to expand, resulting in an increase in buoyancy. This particular section of the marine cable will therefore tend to move upwardly. When a decrease of about 1 pound per square inch below the present pressure level occurs, the pressure comparator activates the control signal FCPLO. This signal is applied through gates G3 and G4 to start the pump motor. The pumping action is continued until the preset pressure is again reached in the float chamber, at which time the diaphragm in the pressure comparator moves to reset the FCPLO signal. If, on the other hand, a particular section of the cable assembly begins to run deeper than intended because the calibration pressure has been set at too high a level or for some other reason, the increased external pressure on the pressure controller unit will be transmitted to the interior of the flotation chamber. The higher pressure within the flotation chamber causes the diaphragm in the pressure comparator to move inwardly toward the calibration chamber. This latter chamber has rigid walls and does not respond to the increased external pressure. Movement of the diaphragm will activate the control signal FCPHI. This signal is transmitted through gate G2 to open the bypass valve. With the valve open, the compressed air in the flotation chamber expels ballast water so that the buoyancy of the cable section increases. This continues until the diaphragm has been forced back to the neutral position, resetting the FCPHI signal and setting the complementary signal FCPHI. At this point, the bypass valve closes and the ballast condition is again stabilized.

It should be apparent from the foregoing that the system of the invention provides an improved method and apparatus for controlling the buoyancy of a marine seismic cable or similar device and that this system can be operated either manually or automatically. Although the particular system described in detail above is the preferred embodiment of the invention, it will be understood that the invention is not restricted to this particular system and that numerous modifications may be made without departing from the scope of the invention. In lieu of maintaining air or gas in the flotation chamber at a pressure in excess of hydrostatic pressure and pumping water into the chamber to reduce the buoyancy of the system, for example, the system may be designed so that the gas is maintained at a pressure less than hydrostatic and water is introduced at hydrostatic pressure by merely opening the bypass valve. Ballast water would be expelled from the flotation chamber in a system of this type by pumping it from the chamber. Similarly, the system may be designed so that the pump operates in both directions and ballast water is both pumped into the flotation chamber to reduce buoyancy and pumped out of the chamber to increase buoyancy. These and other modifications of the system will be apparent to those skilled in the art.

I claim:

1. A method for controlling the buoyancy of a marine seismic cable provided with a lead-in section as said cable is towed through a body of water which comprises monitoring the depth of said cable at a plurality of points along the length of said cable; introducing water from said body of water into at least one of a plurality of buoyancy chambers located at intervals along the length of said cable behind said lead-in section when a reduction in buoyancy is required, each of said buoyancy chambers containing a gas confined to said chamber; and expelling water from at least one of said buoyancy chambers into the surrounding body of water when an increase in buoyancy is required.

2. A method as defined by claim 1 wherein said water is introduced by pumping water into said buoyancy chamber.

3. A method as defined by claim 1 wherein said gas in said buoyancy chamber is maintained at a pressure greater than hydrostatic and said water is expelled by permitting said gas to expand.

4. A method as defined by claim 1 wherein said gas in said buoyancy chamber is maintained at a pressure less than hydrostatic and said water is introduced under hydrostatic pressure.

5. A method as defined by claim 1 wherein said water is expelled by pumping water from said buoyancy chamber into said body of water.

6. A method for controlling the position of a marine seismic cable during seismic prospecting operations carried out in a body of water which comprises towing said cable through said body of water, said cable including a lead-in section fitted with a depth controller; monitoring the hydrostatic pressure on said cable at a plurality of positions along the cable length behind said lead-in section; pumping water from said body of water into at least one of a plurality of individual buoyancy chambers located at intervals along the length of said cable behind said lead-in section in response to a reduction in hydrostatic pressure on said cable, each of said buoyancy chambers containing a gas confined to said chamber at a pressure in excess of hydrostatic pressure; and expelling water from at least one of said buoyancy chambers in response to an increase in hydrostatic pressure on said cable.

7. A method as defined by claim 6 wherein said cable is towed behind a lead-in section fitted with a paravane.

8. A method as defined by claim 6 wherein said water is expelled from said buoyancy chamber by venting said chamber to the surrounding water and permitting said gas to expand.

9. A method as defined by claim 6 wherein said water is expelled by pumping water from said buoyancy chamber into the surrounding water.

10. A method as defined by claim 6 wherein said water is pumped separately into each of a plurality of buoyancy chambers spaced at intervals along the length of said cable.

11. Apparatus for controlling the buoyancy of a marine seismic cable which comprises an outer housing containing an internal buoyancy chamber; an expansion member positioned within said buoyancy chamber for confining a gas within a portion of said chamber; a pump located in said housing, said pump communicating with a water inlet port in the housing wall and with a water discharge port in said buoyancy chamber; means in said housing for actuating said pump; and

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means for connecting said housing in place between adjacent sections of said marine seismic cable.

12. Apparatus as defined by claim 11 wherein said expansion member comprises a collapsible bladder surrounding said discharge port.

13. Apparatus as defined by claim 12 including a bypass valve communicating with the interior of said bladder and with the exterior of said housing and means within said housing for actuating said bypass valve.

14. Apparatus as defined by claim 11 wherein said pump is a reversible pump.

15. A buoyancy controller for use with a marine seismic cable which comprises an elongated outer housing containing an internal buoyancy chamber having a gas inlet near one end thereof and a water inlet near the other end thereof; an elongated inflatable member positioned about said water inlet in said buoyancy chamber; a pump in said housing communicating with said water inlet in said buoyancy chamber and with an inlet port in the outer wall of said housing; a bypass valve in said housing communicating with said water inlet in said buoyancy chamber and with an outlet in the outer wall of said housing; electrical means in said housing for selectively actuating said pump and said bypass valve; and means for connecting said housing between adjacent sections of said marine seismic cable.

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16. A buoyancy controller as defined by claim 15 wherein said electrical means for actuating said pump and bypass valve includes an electric motor connected to said pump, an electric motor connected to said bypass valve, and means for connecting said motors to shipboard control devices.

17. A buoyancy controller as defined by claim 16 wherein said electrical means for actuating said pump bypass valve further includes batteries in said housing and means for connecting said batteries to a shipboard trickle charge source.

18. A buoyancy controller as defined by claim 16 including a pressure comparator in said housing communicating with said gas inlet in said buoyancy chamber, said pressure comparator including a gas pressure calibration chamber, a piston positioned between said calibration chamber and said gas inlet, and switches actuated by said piston for energizing said pump and valve motors.

19. A buoyancy controller as defined by claim 15 including a water filter in said housing between said inlet port and said pump.

20. A buoyancy controller as defined by claim 15 including a hydrostatic pressure sensor in said housing and means for connecting said pressure sensor to a shipboard indicator.

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