[4] Metzner, A. B., "Flow of Non-Newtonian Fluids," Sec. 7, *Handbook of Fluid Dynamics*, edited by V. L. Streeter, McGraw-Hill, New York, 1961.

[5] Wells, C. S., Jr., "On the Turbulent Shear Flow of an Elastico-Viscous Fluid," Paper 64-36, 1964, AIAA; also *AIAA Journal*, Vol. 3, No. 10, Oct. 1965, pp. 1800–1805.

[6] Giles, W. B., "Laminar Viscoelastic Boundary Layers with Roughness," Rept. 64GL51, March 11, 1964, General Electric Co.

[7] Fabula, A. G., "The Toms Phenomenon in the Turbulent Flow of Very Dilute Solutions," *Proceedings Fourth International Congress of Rheology*, Part 3, Interscience, New York, 1965, pp. 455–479.

[8] Hoyt, J. W. and Fabula, A. G., "The Effect of Additives on Fluid Friction," NAVWEPS Rept. 8636, ASTIA AD 612 056, Dec. 1964, Naval Ordnance Test Station, China Lake, Calif.

[9] Shin, H., "Reduction of Drag in Turbulence by Dilute Polymer Solutions," Doctoral thesis, June 1965, Massachusetts Institute of Technology; also *Transactions of the Rheological Society*, Vol. 10, 1966, pp. 335–351.

[10] Gadd, G. E., "Turbulence Damping and Drag Reduction Produced by Certain Additives in Water," *Nature*, May 1, 1965, pp. 463–467.

[11] Patrick, H. V. L., "The Effect of High Molecular Weight Polymer Additives on the Performance of a Conical Diffuser," Paper 66-658, June 1966, AIAA.

[12] Lang, T. G., "Drag of Blunt Bodies in Polymer Solutions, 66-WA/FE-33, 1966, American Society of Mechanical Engineer New York.

[13] Ripken, J. F. and Pilch, M., "Non-Newtonian Pipe Frictio Studies with Various Dilute Polymer Water Solutions," Rept. 7 BuShips Contract S-R009-01-01, June 1964, St. Anthony Fal Hydrodynamics Lab., University of Minnesota.

[14] Pruitt, G. T. and Crawford, H. R., "Effect of Molecula Weight and Segmental Constitution on the Drag Reduction Water Soluble Polymers," DTMB Contract NONR-4306(00 ASTIA AD 625 801, April 1965, The Western Co.

[15] Schlichting, H., *Boundary Layer Theory*, 4th ed., McGraw Hill, New York, 1960, pp. 505, 506.

[16] Ross, D., "Turbulent Flow in the Entrance Region of Pipe," Paper 54-H-89, 1954, American Society of Mechanical E gineers, New York.

[17] Shapiro, A. H., Siegel, R., and Kline, S. J., "Friction Facto in the Laminar Entry Region of a Smooth Tube," *Proceeding 2nd National Congress of Applied Mechanics*, 1954, America Society of Mechanical Engineers, New York.

[18] Astarita, G. and Nicodemo, L., "Velocity Distributions ar Normal Stresses in Viscoelastic Turbulent Pipe Flow," *AICh Journal*, Vol. 12, No. 3, May 1966, pp. 478–483.

[19] von Kármán, T., "On Laminar and Turbulent Friction TM1093, Sept. 1946, NACA; also *Zeitschrift fur Mathematik u Mechanik*, Vol. 1, No. 4, Aug. 1921.

JANUARY 1968 J. HYDRONAUTICS VOL. 2, NO.

# Deep Ocean Work Boat (DOWB), an Advanced Deep Submergence Vehicle

Scott C. Daubin*

*AC Electronics, Division of General Motors Corporation, Santa Barbara, Calif.*

**The submarine will carry two persons to depths of 6500 ft, there to observe and to do work. The spherical pressure hull of HY 100 steel, 82 in. o.d. by 0.935 in. thick is machined inside and out. Spherical symmetry is broken only in hatch areas at the north and south poles. A free flooding fiberglass fairing, 17 ft long by 8$\frac{3}{4}$ ft beam, mounts on pressure hull. The fairing provides a smooth form and contains ballast systems, the propulsion system, manipulator, TV cameras, transducers, and miscellaneous instruments. A cylindrical load skirt provides tie points for the fairing, supports the vehicle when out of water and supports the main batteries. Surface displacement is 16,295 lb; metacentric height is 13 in. surfaced and 5 in. submerged. Lead acid batteries provide 40 kwh of main power. Propulsion drive system utilizes modulating solid-state inverters. An optical system provides pilot and observer full 4-pi solid angle visibility through 180-deg wide angle objectives mounted outboard of ports through hatches. A six-degree-of-freedom manipulator lifts a 50 lb weight at a 49 in. reach. The sonar system provides search, terrain avoidance, upward and downward fathometers, underwater, telephone, and tracking beacon.**

## 1. General

The Deep Ocean Work Boat (DOWB) is a manned undersea vehicle designed to carry two men to depths of 6500 ft, there to do work as its name implies. To carry out its mission it is equipped with an electromechanical manipulator and various viewing and sensing systems that permit it to operate in the black depths near obstacles and potential entanglements.

Presented as Paper 67-370 at the AIAA/SNAME Advanced Marine Vehicles Meeting, Norfolk, Va., May 22–24, 1967; submitted May 19, 1967; revision received October 16, 1967.

* Head, Marine Sciences Section, Sea Operations Department, Defense Research Laboratories.

The philosophy that underlay the design of DOWB ain at producing a large payload-payvolume-depth performa at the minimum expense in weight and size, which w limited by available surface support vessels and the requ ment for both highway and air transportability. Since, of the systems, the pressure hull consumes the single lar share of weight, in its design an attempt was made to minin weight; this was accomplished partly through simplicity the conservation of symmetry.

Table 1 outlines the principal operational characterist Figures 1–4 show the general plane. DOWB's configuratic that of a spherical pressure hull surrounded by a free flooc fiberglass fairing. The prolate spheroid form of the fai is interrupted by the cylindrical main ballast tank penetra

**Table 1 Summary of DOWB characteristics**

| | | | |
|---|---|---|---|
| Displacement | | Crew | 2 |
| Surface (diving trim), lb | 16,295 | Dimensions | |
| Reserve buoyancy | 3,330 | LOA | 17 ft, 0.0 in. |
| Pressure hull | | Beam (extreme) | 8 ft, 8.25 in. |
| Shape | Sphere | Main power | |
| Dimensions, in. | i.d. = 80.174 | Batteries | |
| | $t$ = 0.935 | No. of cells | 120 |
| Material | HY-100 steel | Cell type | Delco Type 847 |
| Collapse, ft | 10,000 | Location | Outboard |
| Failure mode | Plastic instability | Total energy | 40 kwh at 20°C |
| Payload | | Motor (propulsion) | |
| Personnel and effects, lb | 400 | Number | 4 |
| Scientific instruments, lb (and/or ballast) | 800 | Function | 2 horizontal<br>2 vertical |
| Total payload, lb | 1,200 | Power (each shaft), hp | 2 |

Endurance
Speed-Power

| Motor-order | Speed, knots | Propulsion power, kw | Auxiliary power, kw | Endurance, hr | Range, mile |
|---|---|---|---|---|---|
| Full | 2.5 | 5.36 | 1.20 | 6.1 | 15.3 |
| Fast transit | 2.0 | 2.75 | 1.20 | 10.1 | 20.2 |
| Economical transit | 1.5 | 1.16 | 1.20 | 17.0 | 25.5 |
| Search | 1.0 | 0.34 | 1.20 | 25.9 | 25.9 |
| Maneuver | 0.5 | 0.04 | 1.20 | 32.2 | 16.1 |
| Stop | 0.0 | 0.00 | 1.20 | 33.3 | 00.0 |

| Environmental | |
|---|---|
| $O_2$ storage | 126 scf |
| $CO_2$ absorbent | 25.0 lb (LiOH) |
| Atmospheric endurance (nominal) | 65 hrs for 2 men (130 manhours) |

| Environmental sensing: | |
|---|---|
| Direct optical | Ports at north and south poles of sphere. Internal optical system to operator and observe Outboard system above and below for full spherical visibility. |
| TV | TV camera outboard. $3\pi$ solid angle visibility. Double monitor inboard. |
| Illumination | 250-w mercury-vapor lamp. Full train and elevation on bottomside mount. |
| Integrated sonar system | Upward and downward fathometer and underwater telephone. Precision sonar for searc homing, beacon acquisition, and terrain-avoidance. |
| Manipulator system | Six-degrees-of-freedom electromechanical manipulator. 50-lb underwater weight-handlir capability at 49-in. reach. |

vertically about amidships. The pressure hull withstands pressures up to 2860 psi and provides a normal atmosphere for the operators and equipment inside. The fairing provides foundations for the propulsion motors, propulsion controllers, manipulator, shot ballast tanks, vernier ballast bladders, retractable mast, high-pressure-air flasks and piping, sonar transducers, etc. The smooth outer skin also minimizes the danger of entanglement and reduces drag. The load skirt supports the entire vehicle on land and mounts most of the main battery in two concentric rings.

## 2. Drag, Speed, and Power

Using a major dimension of 17 ft and assuming a water temperature of 40°F, DOWB's Reynolds number as a function of speed $V$ in knots becomes†:

$$R = 1.73 \times 10^6 V \qquad ($$

Reference 1 reports that a wetted surface drag coefficient 0.027 was useful in the case of the data recovery vehic ALVIN. This same coefficient is used to predict DOWB dr characteristics. Justification for the application of ALVIN drag coefficient to DOWB is based on 1) similarity in lengt to-beam ratios, ALVIN—2.52 (approx), DOWB—2.32; similarity in Reynolds number region; and 3) insensitivity ALVIN drag resistance to hull shape, as reported in Ref. Thus using DOWB's calculated wetted surface of 461 ft² t following expression is obtained for drag resistance as a fur tion of speed $V$ in knots:

$$R_f = 35.51 V^2$$

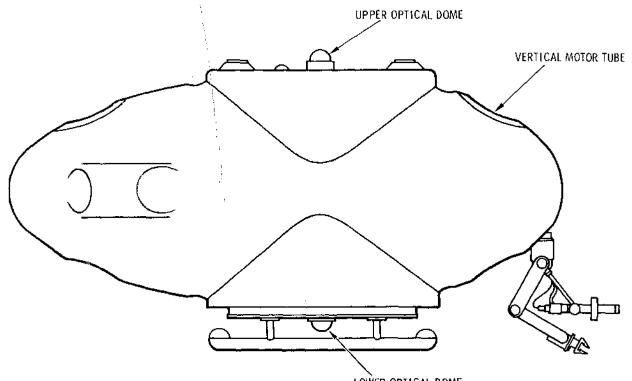


**Fig. 1 DOWB outboard profile.**

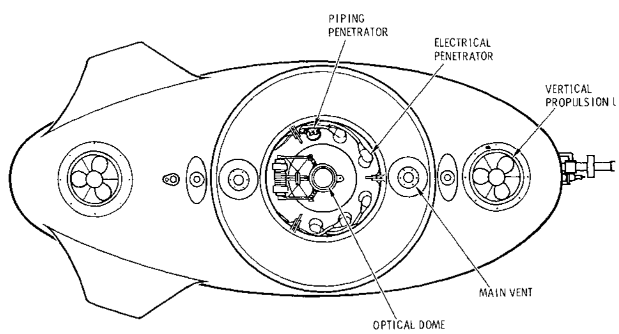


**Fig. 2 DOWB outboard deck plan.**

† For Eqs. (1–4) see, for example, Ref. 2.

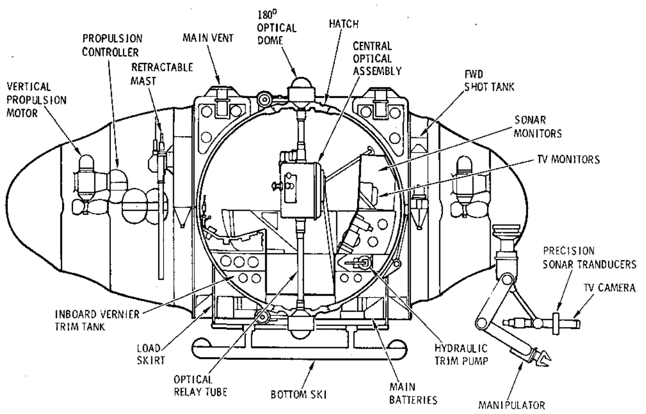


**Fig. 3 DOWB inboard profile.**

Equation (2) permits calculation of effective horsepower:

$$\text{ehp} = 0.109V^3 \tag{3}$$

References 2 and 3 were used to calculate propeller efficiency and hull efficiency. At 3 knots the following numbers were found:

| | |
|---|---|
| Bare propeller efficiency | = 0.335 |
| Shroud efficiency correction‡ | = +0.076 |
| Net propeller efficiency | = 0.411 |
| Hull efficiency§ | = 0.960 |
| Propulsive coefficient | = 0.395 |

This propulsion coefficient with Eq. (3) produces the shaft horsepower-speed function (where $V$ is in knots),

$$\text{shp} = 0.276V^3 \tag{4}$$

Drag, effective and shaft horsepower, Eqs. (2–4), are plotted in Fig. 5.

## 3. Pressure Hull

Retention of symmetry and simplicity were designed objectives of the spherical pressure hull, Fig. 6. Such efficiencies of design would produce a high operating depth-to-weight ratio, 1.028 ft/lb; furthermore, the elimination of any optical viewing port from the shell matched well the requirements of the new optical system discussed in the section below. The viewing ports are located in the centers of the hatches that are found at the poles of the sphere. The only remaining deviations from spherical symmetry are six conical penetrations arranged about the upper hatch in the thickened section of the hatch insert forging; five of these penetrations are for electrical penetrators of 37 conductors each, and one is for a piping penetrator of two channels.

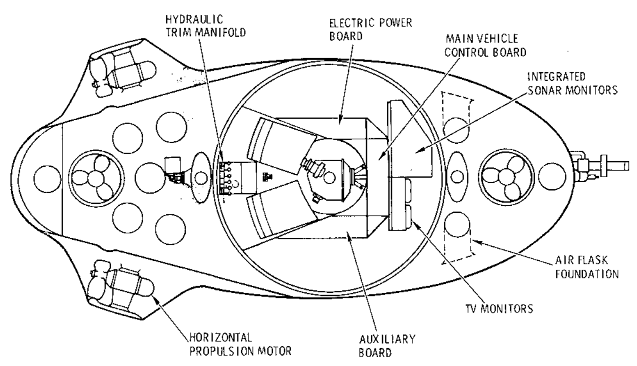


**Fig. 4 DOWB inboard deck plan.**

‡ Based on a calculated propeller load coefficient $(T/\rho A v_0^2)$ of 1.95.

§ Based on a 15° cant of propeller shafts to $C/L$ axis.

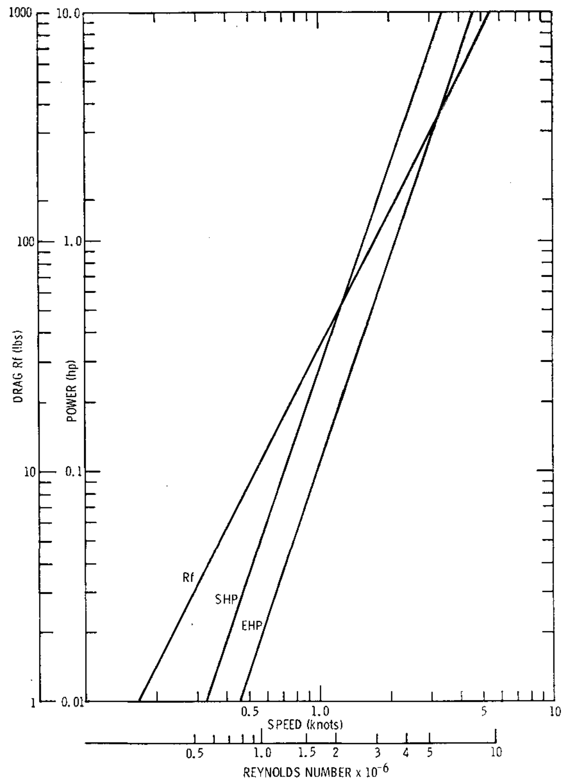


**Fig. 5 DOWB speed, drag and speed, power characteristics.**

The pressure hull was fabricated from six principal pieces of HY 100 steel. Two were the hemispherical spun heads; two were the hatch insert forgings; and two were the hatch forgings. The shell hemispheres were spun from 1.5-in. plate. They were then machined inside to near the final dimensions, welded together at the equator, then machined inside and outside to the final dimension. The hatch insert forgings were machined inside and out and then welded to the polar regions of the sphere. Thus only three principal welds

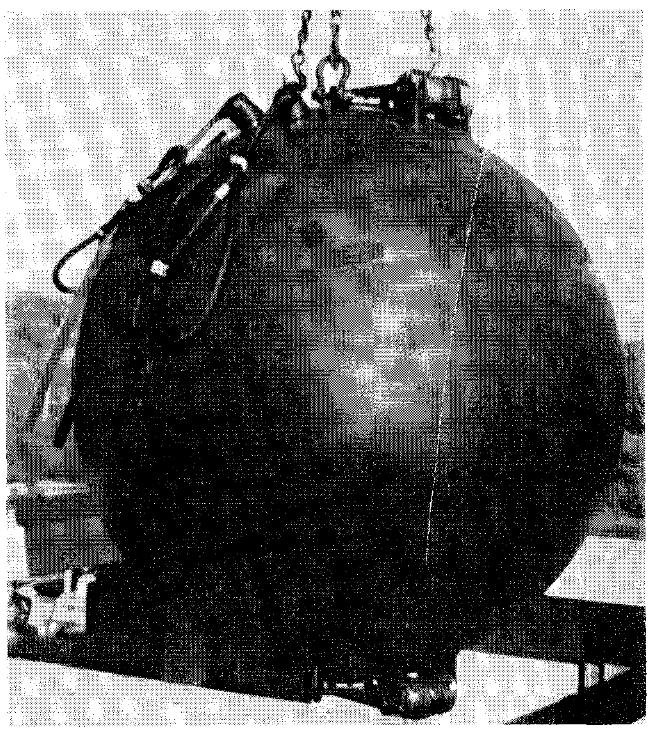

**Fig. 6 DOWB pressure hull during pressure test operations.**

**Table 2 Physical properties of DOWB HY 100 pressure hull material before and after stress-relief**

| No. | Item Tested | Physicals before stress-relief Yield | Tensile | % El. | R/A | Physicals after stress-relief Yield | Tensile | % El. | R/A |
|---|---|---|---|---|---|---|---|---|---|
| I. *Welding proc. test plate* | | | | | | | | | |
| $p^a$ | Mill test report | 109,100 | 123,900 | 22 | 66.5 | | | | |
| $w$ | 0.904 reduc. sect tensile | 120,575 | 130,531 | 19 | ... | 121,381 | 133,073 | 13 | |
| $w$ | 0.898 reduc. sect tensile | 124,722 | 132,238 | 15 | ... | 117,453 | 133,370 | 11 | |
| $p$ | 0.505 reduc. sect tensile (hemisphere parent) | 132,867 | 140,360 | 20 | 63.5 | | | | |
| $w$ | Side bends | | OK | | | | OK | | |
| $p$ | Charpy's (mill) | | 60–62–64 at −120°F | | | | | | |
| $p$ | Charpy's (H&C)[b] | | 32.5–32.5–39.5 at −120°F | | | | | | |
| $w$ | Charpy's (H&C) | | 38–42–44 at −60°F | | | | 24–25–25.5 at −60°F | | |
| II. *Hatch insert forging* | | | | | | | | | |
| $p$ | Mill test report | 104,000 | 120,600 | 21 | 70 | | | | |
| $p$ | Mill test report | 104,500 | 121,000 | 22 | 70 | | | | |
| $p$ | Tensile 0.506 reduc. sect | | | | | 126,866 | 137,065 | 19 | 64.8 |
| $p$ | Charpy's (mill) | | 51.5–61–60.5 at −120°F | | | | | | |
| $p$ | Charpy's (mill) | | 58.5–63–66 at −120°F | | | | | | |
| $p$ | Charpy's (H&C) | | | | | | 17–19–23 at −120°F | | |
| $p$ | Side bends | | | | | | OK | | |
| III. *Hatch cover forging* | | | | | | | | | |
| $p$ | Mill test report | 103,000 | 119,200 | 20 | 65 | | | | |
| $p$ | Mill test report | 103,200 | 119,400 | 22 | 71 | | | | |
| $p$ | Tensile 0.357 reduc. sect | | | | | 102,000 | 117,700 | 21.0 | 66.0 |
| $p$ | Charpy's (mill) | | 58–66.5–68 at −120°F | | | | | | |
| $p$ | Charpy's (mill) | | 57.5–58–61.5 at −120°F | | | | | | |
| $p$ | Charpy's (H&C) | | | | | | 21.5–24.0–27.0 at −120°F | | |
| $p$ | Side bends | | | | | | OK | | |

[a] $p$ denotes test made on parent metal; $w$ denotes test made on welded specimen.
[b] Hahr and Clay.

were made, the equatorial weld and two girth welds at latitudes of approximately 60° north and south. Welding was in accordance with Navy instructions for HY 80 steel; only certified welders worked, electrodes were carefully conditioned and handled, the hull was preheated, and once a weld was started and the root pass inspected, welding was continued without interruption until completion of the joint. The hull was rotated on trunions to permit complete downhand welding. Each weld was inspected by three methods, magnetic particle, x-ray, and sonic.

The entire hull and hatches were stress-relieved at 1010°F for one hour. Because of their increased thickness, the insert forgings and hatches had previously been stress-relieved alone for one hour. Impact, bend, and tensile samples were stress-relieved along with the sphere; results are shown in Table 2.

After stress-relieving the sphere was subjected to a detailed measurement program. The critical arc length as discussed by Kiernan[6] is 14.9 in. The sphericity of the outer surface was checked with a special fixture, a sliding-arc bridge gage machined to a radius equal to the nominal outer spherical radius plus the standoff distance; its length of arc was about 14 in. A spherical deviation of 0.025 in. corresponds to a mean local radius of 43.4 in. over a critical arc length; this implies that inelastic instability would occur at 10,200 ft. After final machining of the sphere, 288 sets of sphericity readings, both meridianal and latitudinal, were taken over the surface of the sphere. The maximum deviation measured was 0.012 in.

An arm pivoted at the center of the sphere measured the radius at each three degrees of latitude between 69°N and S on each of eight meridians. At each measurement point shell thickness was measured sonically. These measurements, summarized in Table 3, confirm that the pressure hull is a remarkably precise sphere, having a standard deviation of only 0.009 in. in a radius of 40 in. Because deviations from sphericity can cause significant reductions in the depth of shell buckling, such precision of fabrication is necessary in a deep diving vehicle.

The full-scale test and analysis program,[4] predicts collapse pressures and modes as follows: 1) elastic collapse of spherical shell, 29.545 ft; 2) yield collapse of spherical shell, 11,705 ft; and 3) instability initiated by ending at hull-insert joint, 10,000 ft. Mode 3 is the expected failure mechanism and 10,000 ft is the predicted depth.

**Table 3 DOWB pressure hull shell measurement summary[a]**

| Longitude | Radius, in. Maximum | Minimum | Average | Std. dev. | Thickness, in. Maximum | Minimum | Average | Std. dev. |
|---|---|---|---|---|---|---|---|---|
| 000 | 40.097 | 40.031 | 40.086 | 0.011 | 0.932 | 0.907 | 0.921 | 0.008 |
| 045°W | 40.099 | 40.056 | 40.087 | 0.009 | 0.946 | 0.916 | 0.939 | 0.007 |
| 090°W | 40.099 | 40.065 | 40.089 | 0.007 | 0.950 | 0.921 | 0.942 | 0.007 |
| 135°W | 40.097 | 40.064 | 40.086 | 0.006 | 0.941 | 0.911 | 0.931 | 0.006 |
| 180 | 40.097 | 40.055 | 40.087 | 0.009 | 0.941 | 0.905 | 0.930 | 0.007 |
| 135°E | 40.097 | 40.058 | 40.084 | 0.008 | 0.948 | 0.914 | 0.939 | 0.008 |
| 090°E | 40.097 | 40.047 | 40.087 | 0.009 | 0.945 | 0.917 | 0.936 | 0.006 |
| 045°E | 40.102 | 40.046 | 40.090 | 0.010 | 0.950 | 0.911 | 0.940 | 0.007 |
| Net | 40.102 | 40.031 | 40.087 | 0.009 | 0.950 | 0.905 | 0.935 | 0.007 |

[a] Readings were taken every 3° of latitude between 60°N and 60°S on each indicated meridian. A total of 41 readings for each meridian and 328 readings for spherical shell were taken.

Table 4 Buoyancy and trim systems summary

| System | Type variable Wt. | Type variable Disp. | Buoyancy mat'l. | Buoyancy range Weight, lb | Buoyancy range Moment, ft-lb |
|---|---|---|---|---|---|
| Main Ballast (reversible) | x | | Water | 3330 | 0 |
| Vernier Trim (reversible) | | x | Oil | 512 | Fwd. 240<br>Aft 320 |
| Shot Ballast (Nonreversible) | x | | Iron shot | 900 | Fwd. 1535<br>Aft 1535 |

## 4. Buoyancy and Trim Systems

Three systems are provided by which the net buoyancy of the submarine may be varied. Table 4 summarizes the characteristics of these systems.

1) The main ballast system with a displacement of 3330 lb provides about 20% surface reserve buoyancy. The tank is flooded by opening the two motor-operated, main vent valves in the tank top. The tank is dewatered by blowing with hp air through solenoid operated valves.

2) The vernier trim system provides for precise and reversible adjustments in submerged displacement. It is used primarily for acquiring and maintaining a neutral trim, or a trim as otherwise specified, at the operating depth. It consists of the central trim tank in the pressure hull, the forward and aft trim bladders, the hydraulic trim pump, and associated piping, valves, and fittings. To increase displacement, and hence buoyancy, oil is pumped from the tank to the bladders; to decrease displacement oil is bled back into the tank from the bladders. Fore and aft trim may be adjusted through a range of $\pm 2.5°$ by transferring oil between the bladders.

3) The shot ballast system provides for compensating variations in loading between dives and for the application of net negative or positive buoyancy during deep descents or ascents for the purpose of conserving battery energy. A motor-driven ball stop meters shot out of the two tanks.

In emergencies various items can be jettisoned either to acquire buoyancy or to extricate the vehicle from entanglements. The two 120-v main batteries can be dropped separately, each providing about 750 lb of positive buoyancy. Should the shot-metering mechanism fail, the shot tanks can be dropped as units. The manipulator can be jettisoned in event of entanglement. A protective cover and an arming switch protects all emergency release controls from inadvertent operation. Three separate sources of power are available to operate the emergency circuits: the emergency battery, which has no other function; the auxiliary battery; or a spare battery which may be tied into the system through terminal posts.

## 5. Energy Storage, Conversion, and Distribution

Energy is supplied by three functionally distinct batteries, the main battery, the auxiliary battery, and the emergency battery. The main battery provides electrical energy for the propulsion system and most of the d.c. loads internal to the pressure hull and most of the a.c. loads via the main d.c./a.c. inverters. The auxiliary battery supplies low-voltage d.c. circuits which require a separate source and backs up the main battery through the emergency d.c./a.c. inverter; the hydraulic trim pump motor is the heaviest load supplied by the auxiliary battery. The emergency battery provides power to the emergency release system exclusively. The main battery is located outboard; the auxiliary and emergency batteries are located inboard in the pressure hull.

Table 5 outlines the characteristics of the principal battery systems.

The main battery consisting of two separate 120-v batteries is supported by the load skirt in two concentric rings. These separate batteries are named "inner" and "outer" in accordance with their position relative to the load skirt. The electrically independent inner and outer main batteries may be paralleled through the main propulsion and switching circuit.

Each main battery consists of ten 12-v batteries connected in series. Each 12-v battery consists of six separate cells whose cases and tops are molded of unplasticized, Type I polyvinylchloride by the intrusion process.[5] Copper bussing connects the cells together rigidly and permanently to form a 12-v battery; these intercell connections are jacketed with molded polyurethane. The entire battery then receives a molded polyurethane protective jacket. Thus insulated, the batteries are immersible in seawater. Heavy-duty (60 amp), in-line, pressure-proof, underwater connectors connect to the end terminal to permit "unplugging" of the 12-v batteries from one another for removal and maintenance. A fiberglass battery tray contains each 12-v battery and provides means for attaching to the load skirt. A dielectric oil supplied from a central reservoir through a header manifold floats over the electrolyte. Gas escaping from each cell rises to the header, on the way passing through a baffle assembly to separate electrolyte carried over, and then passes to the reservoir and, after sufficient volume has been collected and pressure built up, out the gas bleed valve.

The 120-v d.c. is converted to 115, 60-cycle, single-phase a.c. by two solid-state inverters of 400 w rated load each (500 w intermittent). An emergency 100-w inverter, for use when the main batteries are gone, is powered from the auxiliary battery. Alternating current circuits have the selection choice of any of the following three 115-v, 60-cycle, single-phase inverters: No. 1, No. 2, or emergency. In addition, there are two special-purpose inverters, one that powers the 250-w, mercury-vapor search lamp from the main battery and one that powers the 400-cycle, three-phase, directional gyro from the auxiliary battery.

Five electrical penetrators lead power and signal circuits through the pressure hull. Each penetrator contains 37 conductors: 29 American wire gage 16 leads, four American wire gage 14 leads, and two coaxial cables RG-186 A/U.

## 6. Main Propulsion

Four ducted main propulsion motors provide four degrees of maneuvering freedom to the vehicle, i.e., fore and aft thrust, vertical thrust, yaw twist, and trim twist. Two "horizontal" propulsion units are in the deck plane of the vehicle, canted outboard at 15°. Two "vertical" units are located fore and aft with their axes normal to the deck plane. The propulsion motors deliver 2 shp to 18-in.-diam propellers at 486 rpm.

Table 5 DOWB battery characteristics

| | Main battery | Auxiliary battery | Emergency battery |
|---|---|---|---|
| Type | lead-acid | silver-zinc | alkaline |
| volts (O.C.) | 120 | 30 | 30 |
| amp-hr | 366 | 72 | |
| kwh | 40 | 1.82 | |
| Number cells | 120 | 16 | 5 |
| Mfg. and model no. | Cell elements: Delco type 847<br>Cases: AC-DRL special development | Yardney Model HR-72 | Eveready Model 520 |

Figure 7 shows one of the oil-filled, pressure-compensated, three-phase induction propulsion motors. A pressure compensating system pressurizes the internal volume of the motor 5 psi in excess of ambient to insure that any seal leakage will be outward; an oil reservoir on each motor contains a 5% reserve volume. A planetary 6.25:1 speed reducer is driven by the motor armature and drives the output shaft on which the propeller mounts. The speed reducer, a development of the General Motors Research Laboratories,[7] known as the "friction drive" resembles a planetary reduction gear with one major exception, i.e., there are no gears, only wheels and rings with smooth contact surfaces. Friction between the elements develops the output torque. An essential feature of the GM friction drive is that the interelement contact friction is a function of the output torque, thereby providing high efficiencies at low torque levels and the capability of generating large output torques with no slippage. High efficiency and low radiated noise are the virtues of this speed reducer of most importance in this application.

Each propulsion motor is driven through a propulsion controller (Fig. 8) housed within its own pressure vessel in the fairing. The propulsion controller mediates among three elements, the operator, the power source, and the motor. It receives speed and direction command signals electrically from the operator in the pressure hull, receives actual speed signals from the motor and converts the 120-v d.c. voltage from the battery to a three-phase, a.c. driving signal of the proper frequency to drive the motor. The controller unit automatically adjusts phase rotation frequency to maintain a constant slip frequency with respect to armature rotation speed, thus producing high motor efficiency throughout all speed ranges, high starting torque, and short response time.

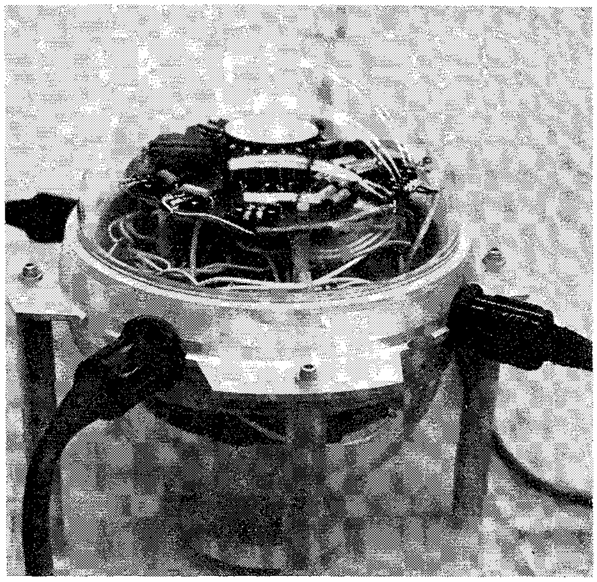

Fig. 8 DOWB propulsion controller.

## 7. Sensing Systems

Three environmental sensing systems, the optical system, the TV system, and the integrated sonar system, provide to the operators information on the vehicle's environment.

### Optical System

A pressing need in the design of underwater vehicles is improved viewing capability, i.e., field of view, visual acuity, and operator comfort. DOWB's optical system, interposed between the external light field and the observer, brings the image to the observer rather than vice versa, which is the rule in most existing vehicles. DOWB's observers view the surroundings from a comfortable seated position. The system provides full hemispheric visibility, top or bottom, for each of two observers. The optical axis is coincident with the polar axis of the spherical pressure hull. An optical dome containing a 180° wide angle lens assembly is mounted on the outboard side of each hatch, as shown in Fig. 9. Light gathered by the dome is refracted and transmitted through the plexiglass port in the center of the hatch, into the optical relay tube, and into the central optical assembly where it is formed into separate images for each observer. The arrangement of the optical system is shown in Fig. 3. Each observer may choose independently to see the "upper" or "lower" hemispheres. The observers' field is similar to a plan position indicator (PPI) presentation in that it represents an area with the vehicle at the center. Relative bearing in the image field represents relative bearing of the object; radial distance however represents zenith (or nadir) angle, from 0° at the center to 90° at the edge of the field. A removable sunshade which blocks out the sun through 90° in bearing and all elevations above 45° may be inserted into each eyepiece. An illuminated reticle marks every 30° of bearing and every 30° of zenith angle.

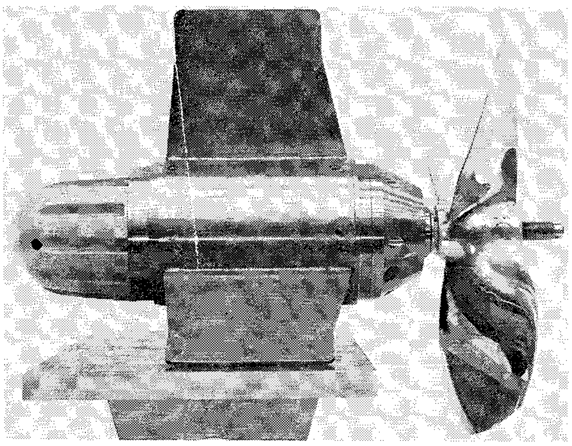

Fig. 7 DOWB propulsion motor.

### Integrated Sonar System

Because seawater is relatively transparent to acoustical energy, sonar provides the primary means of underwater detection and communication. The integrated sonar system

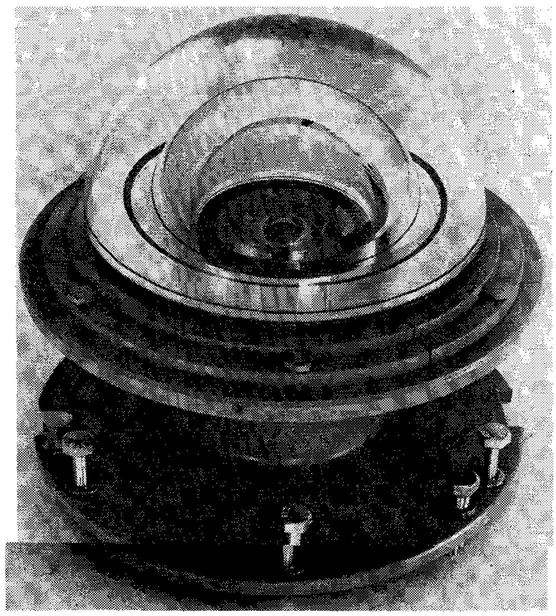

Fig. 9 DOWB optical dome.

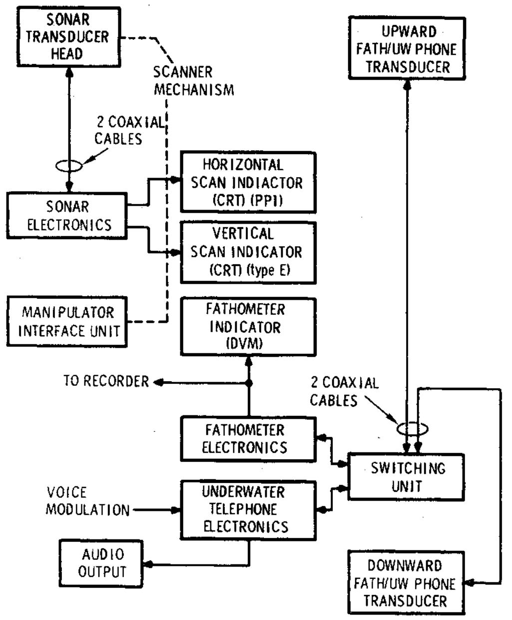


**Fig. 10 Block diagram DOWB integrated sonar system.**

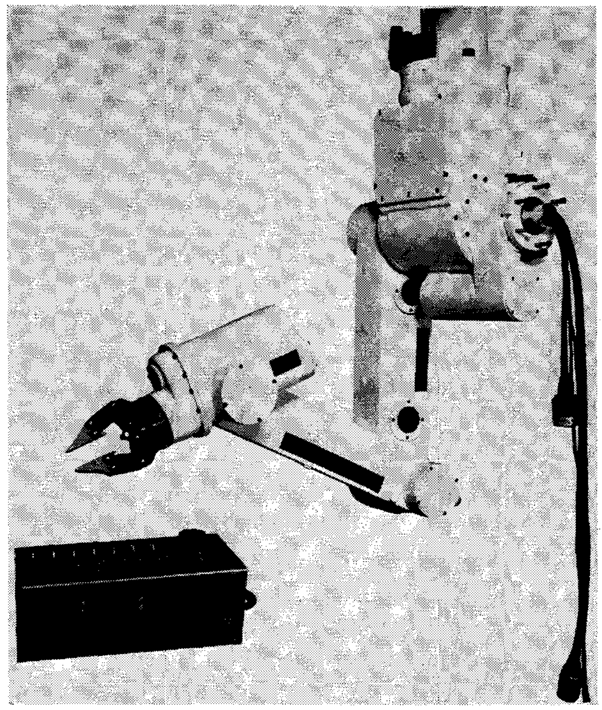

**Fig. 11 DOWB manipulator.**

contains the following units: precision sonar, underwater telephone, fathometer, and beacon. Figure 10 is a block diagram of the integrated sonar system; Table 6 summarizes system characteristics.

The precision sonar is used for small-object location, terrain-avoidance, navigation, mapping, and beacon (or transponder) acquisition. It operates two beams in the "searchlight" mode, a vertical "fan" which indicates in a PPI scope, and a "pencil" beam which indicates in a Type E scope (range vs elevation angle). The vertical fan searches in azimuth; the pencil beam examines targets and terrain in vertical section. Transducers for both beams mount on the manipulator assembly on the TV camera; they train with the manipulator but elevate independently of the arm. A selector switch on the operator's console chooses one of two mechanical modes of operation, manual or automatic scan. In manual training is under the control of the manipulator operator through the manipulator control box; in automatic scan the entire manipulator assembly (with the transducers) will train back and forth over a 30° or 340° azimuth range at any chosen central bearing.

The underwater telephone and fathometer share the upwar and downward beaming transducers. A selector interloc system connects the last unit chosen to the desired transduc and reverts any unit that was previously connected thereto t "standby." The fathometer indication is a digital readou that contains an attachment point for an analog recorde A "false bottom" discriminator circuit prevents any rea ings less than a preset depth interval; thus with an a proximate knowledge of the distance to the bottom or tl surface, spurious reflective layers can be ignored.

### TV System

As seen in Figs. 3 and 11, a television camera and unde water light attach to the auxiliary flange of the manipulat assembly; they train with the manipulator but elevate i dependently of the arm. The camera covers a field well ov

**Table 6 Integrated sonar characteristics**

| | Precision sonar | | | | |
|---|---|---|---|---|---|
| | Azimuth beam | Elevation beam | Fathometer | U/W Telephone | Beaco |
| Carrier frequency, kHz | 225 | 175 | 30 | 8.05 | 16 |
| Modulation | PM (P1) | PM (P1) | PM (P1) | FM (F3) | PM (P |
| Pulsewidth, msec | 0.5 | 0.5 | 10 | | 4 |
| Pulse rep. rate, pps | Variable (See Below) | | 0.33 | | 0.1 |
| Output power (peak, acoustic), w | 100 | 10 | 1 | 6 | 10 |
| Receiver bandwidth, kHz | 20 | 20 | 3 | 2 | |
| Beamwidth, (°) | 3 × 45 | 3 × 3 | Up—30 (cone)<br>Down—10 (cone) | Up—180<br>Down—180 | 45 (cor |
| Display | Type P(PPI) Type E<br>(7 in. CRT, P7 Phosphor) | | Digital voltmeter<br>(1 in. res.) | Speaker | |
| Range capability, yards | 570 on 0.1 sq. yd target<br>1500 on beacon | | | | |
| Range scale/scan rate/<br>pulse rep. rate<br>(yards/deg/sec/pps) | 1000/3/0.835<br>500/5/1.67<br>100/25/8<br>50/50/160 | | | | |
| Notes | Auto Scan Sectors<br>340°<br>30° at any angle | | | Compatible with UQC | 7 day l |
| Maximum power drain, w | 273 | | 70 | 100 | |

**Table 7 TV system equipment**

| | |
|---|---|
| Camera | Vidicon OEC Model 110 |
| Monitor | 9-in. Sony Model PVJ-3040 |
| U/W Light | 250-w mercury-vapor OEC Model LDC-250 |

a hemisphere in solid angle; it thus views an otherwise blind laminar volume between the upper and lower optical fields. Two 9-in. monitors are provided; the second will serve a second camera that can be mounted aft. For launching and recovery the camera along with the "forearm" of the manipulator are housed in the vertical motor tube; the underwater light is removed. Table 7 lists the DOWB's present TV system hardware.

## 8. Manipulator

As armament is to a military submarine, so the "arm" is to a submersible work boat; it is essential to the accomplishment of the primary mission. DOWB has an electromechanical manipulator with six degrees of freedom, as shown in Fig. 11. In event of entanglement the oil-filled, pressure-compensated manipulated is jettisonable. In addition to the arm, the manipulator mounts an auxiliary flange opposite to the shoulder pivot. The auxiliary flange, training with the manipulator but elevating independently, provides a mounting for the TV camera, underwater light, and precision sonar transducers; Fig. 11 shows the cabling for these units extending through the auxiliary flange. A two-speed switching circuit, powered from the 120-v main battery and the 30-v auxiliary battery, controls all six arm functions plus the elevation of the auxiliary flange. Table 8 summarizes manipulator functions and capabilities.

## 9. Atmospheric Control

The atmospheric control systems consist of the oxygen replenishment system, the $CO_2$ removal system, the humidity and temperature control system, and the atmospheric monitoring system. The oxygen replenishment and $CO_2$ removal systems operate together. Oxygen is supplied from a high-pressure flask through a reducing valve, a flow control valve, a rotameter flow indicator and then to the atmosphere. Carbon dioxide is removed in a forced ventilated scrubber stack containing lithium hydroxide. Assuming 100% $CO_2$ removal, the

**Table 8 Manipulator characteristic summary**

| Degree of freedom | Angular limits | Angular indication | Speed, Etc. |
|---|---|---|---|
| Shoulder rotation | 370° | Yes | 2.5 rpm |
| Shoulder pivot | 320° | Yes | 2.0 rpm |
| Elbow pivot | 320° | Yes | 2.1 rpm |
| Wrist pivot | 328° | Yes | 2.2 rpm |
| Wrist rotation | Continuous | No | Torque-8 in. lb<br>Speed-5 rpm |
| Hand grip | ... | No | Travel-0–4 in.<br>Force-0–120 lb<br>Speed-35in./min |
| Auxiliary flange | 340° | Yes | Torque-160 in. lb<br>Speed-1.9 rpm |

| Weights, lb | Air | Water |
|---|---|---|
| Dry | 153 | |
| Fluid filled | 185 | 105 |

Reach (shoulder axis to finger tips) = 49 in.
Weight-handling capacity (at maximum reach) = 50 lb

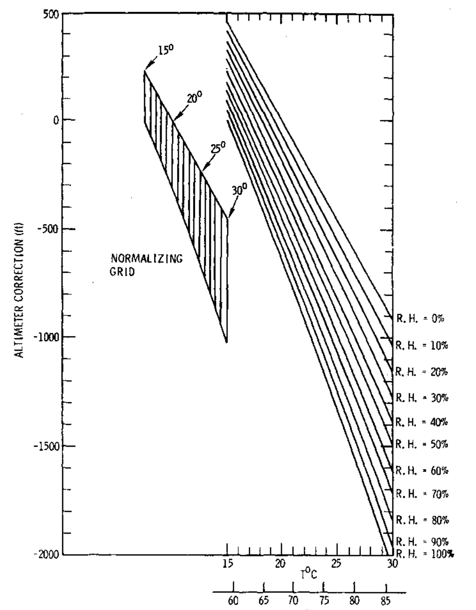


**Fig. 12 DOWB pressure hull altimeter correction for temperature and relative humidity.**

control objective is to supply just enough oxygen to replace that which is removed by metabolism. The monitoring instruments keep track of the atmospheric composition. The basic instruments are a continuously reading, oxygen-concentration indicator; a thermometer; a continuously reading hygrometer; and an aircraft altimeter that summarizes the net effects in terms of pressure. Since the scrubber capacity is large and its efficiency is high, carbon dioxide and carbon monoxide are monitored intermittently by hand-operated instruments. Air forced through a desicant stack keeps humidity low.

The altimeter is a sensitive indicator of change. For DOWB's pressure hull volume of 140 ft$^3$ a 1% increase in oxygen or carbon dioxide percentage will cause a decrease in altitude of 277 ft. Unfortunately, temperature and relative

**Table 9 DOWB atmospheric control system characteristics**

| | | |
|---|---|---|
| DOWB interior volume, nominal | 140 ft$^3$ | |
| Nominal respiration rates | Per man | Per 2 men |
| $O_2$ | 1.0 scf/hr | 2.0 scf/hr |
| | 186 scc/min | 372 scc/min |
| $CO_2$ | 0.8 scf/hr | 1.6 scf/hr |
| | 149 scc/min | 298 scc/min |
| $CO_2$ scrubbing effectiveness | | |
| Chemical absorption at 60% eff. | LiOH 4.46 scf/lb | |
| | NaOH 2.68 scf/lb | |
| Scrubber flow rate | 20 scf/min | |
| Atmosphere change time | 7 min | |
| Atmospheric replenishment chemical supply | | |
| $O_2$ (in 2 Q80SCF flasks) | 160 scf | 160 man hours |
| LiOH[a] | 25 lb | 139 man hours |
| NaOH[a] | 40 lb | 134 man hours |
| Instrumentation | | |
| $O_2$ indicator | Teledyne Inc. TAI Series Model 320 cell, Type B-1 | |
| $O_2$ flowmeter | Brooks instrument, Rotameter Model 1110 Sapphire Float Scale 50–500 scc/min | |
| $CO_2$ indicator | Scott Draeger Ch 251 (1%)<br>Ch 235 (0.1%) | |
| CO indicator | Scott Draeger Ch 289 | |

[a] Either LiOH or NaOH is used, not both

**Table 10 DOWB component pressure test summary**

| Equipment | No. cycles | Max. pressure, psig | Notes |
|---|---|---|---|
| Pressure hull | 4 | 3300 | Ref. 4 |
| | 10 | 3000 | |
| Propulsion pressure vessels | 5 | 4400 | |
| Pressure transducer housings | 2 | 3300 | |
| Penetrators, electrical | 2 | 5000 | 12 hour soak at 5000 psi |
| Penetrators, piping | 4 | 3300 | With pressure hull |
| | 10 | 3000 | |
| Inboard pressure piping | 2 | 4400 | |
| Main Batteries | 1 | 3000 | Discharged at pressure |

humidity also cause indicated altitude changes. Figure 12 provides a means for calculating altimeter corrections for changes in temperature and relative humidity in order that the effects of gas concentration changes may be found. Since the corrected altimeter reading is the most sensitive indicator of atmospheric conditions, oxygen flow rate is adjusted in response to this instrument. Oxygen-concentration readings are used to confirm the purity of the atmosphere. Table 9 summarizes the atmospheric control system performance characteristics and hardware.

## 10. Handling

Three lifting eyes attached to the pressure hull at the top hatch insert forging permit handling by crane. Four additional items of detachable equipment serve handling functions but do not offer parasitic weight during operations. 1) Towing frame provides towing eye forward; 2) spreader bar provides hard handling eyes outboard of beam amidships; 3) freeboard extender, lower, increases freeboard to 57 in. for personnel transfer in seaway using top hatch; and 4) freeboard extender, top, completely encloses portable fairwater to permit opening of top hatch in seas that otherwise would swamp the vehicle.

## 11. Quality Assurance Program

Quality is assured by instruction, inspection, documentation, and test. The following procedures were invoked:

1) Engineering specifications were issued for major systems and components, including pressure hull, hatches, fairing, internal structure, optical system, manipulator, and propulsion system. These specifications required specific material certification and inspection documentation, written manufacturing procedures, and testing. In the case of the pressure hull, an independent inspection agency was retained to provide detailed inspection and certification during the manufacturing period.[4]

2) Contractor specifications were required on other systems, including sonar, T. V., inverters, and underwater lights.

3) Formal, controlled working plans were used for the manufacture of parts and assemblies.

4) A shop test program requiring formal test reports was followed. This included inspection, operational, and pressure testing. Table 10 summarizes the pressure test program.

5) Sea trials are to be conducted. These include ballasting and trim, dock trials, underway surface trials, towing and handling, personnel transfer, shallow submergence, surface and submerged propulsion, jettison trials, replenishment at sea (battery and air charging, chemical resupply), air revitalization, annd deep submergence.

## References

[1] Mavor, J. W., Jr. et al., "Alvin, 6000-Ft Submergence Research Vehicle," Annual Meeting Paper 3, 1966, Society of Naval Architects and Marine Engineers.

[2] Attwood, E. L. and Pengelly, H. S., *Theoretical Naval Architecture*, 1956, Longmans, Green.

[3] Rossell, H. E. and Chapman, L. B., *Principles of Naval Architecture*—Vol. II, 1958, Society of Naval Architects and Marine Engineers.

[4] Briggs, E. M., Jones, J. J., and DeHart, R. C., "Fabrication Inspection and Experimental Stress Analysis for the Deep Ocean Work Boat," Jan. 1967, Southwest Research Institute.

[5] Usab, M., "'Intrusion' is a Versatile New Process for Thermoplastics," Technical Rept. 66, Oct. 1960, Western Plastics.

[6] Kiernan, T., "Predictions of the Collapse Strength of Three HY 100 Steel Spherical Hulls Fabricated for the Oceanographic Research Vehicle 'ALVIN'," Rept. 1792, March 1964, David Taylor Model Basin.

[7] Hewko, L. O., "GMR Silent Planetary Friction Drive Speed Reducers," Rept. GMR 398, 1963, General Motors Research Laboratories.