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NUSC Technical Report 6115

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The Effects of Hydrostatic Pressure On Synthetic-Rope Buoyancy In Fresh and Salt Water

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16 November 1979

NUSC
Naval Underwater Systems Center
Newport, Rhode Island • New London, Connecticut

Preface

This report was prepared under the Ocean Measurements and Array Technology (OMAT) portion of the SEAGUARD Project sponsored by the Defense Advanced Research Projects Agency (ARPA Order No. 2976), Program Manager, R. Cook, Tactical Technology Office; NUSC Project No. A-696-00, Program Manager, B. Cole.

The Technical Reviewer for this report was B. Cole, Code 3104.

REVIEWED AND APPROVED: 16 November 1979

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New London, Connecticut 06320.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NUSC TR-6115 (14)
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): THE EFFECTS OF HYDROSTATIC PRESSURE ON SYNTHETIC-ROPE BUOYANCY IN FRESH AND SALT WATER
5. TYPE OF REPORT & PERIOD COVERED: Technical rept.
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): Gary T. Griffin; William A. Watkins, LT. USN
8. CONTRACT OR GRANT NUMBER(s): ARPA Order-2976
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Underwater Systems Center, New London Laboratory, New London, CT 06320
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: A-696-00
11. CONTROLLING OFFICE NAME AND ADDRESS:
12. REPORT DATE: 16 Nov[redacted]79
13. NUMBER OF PAGES: 16
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
    - Project SEAGUARD
    - Synthetic Ropes
    - Hydrostatic Pressure
    - Buoyancy
    - Bulk Modulus
    - Compressibility Effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Tests were conducted to determine the effect of hydrostatic pressure on the buoyancy of a large diameter synthetic rope. This report presents the results of those tests and discusses their meaning in terms of the compressibility effects of the rope material and the deep ocean environment.

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S/N 0102-014-6601

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THE EFFECTS OF HYDROSTATIC PRESSURE ON SYNTHETIC-ROPE BUOYANCY IN FRESH AND SALT WATER

INTRODUCTION

In some deep-ocean applications, the use of buoyant rope to suspend articles above the ocean bottom may be less expensive than the use of attached buoyancy modules (e.g., syntactic foams, glass balls, etc.).

To ascertain the feasibility of buoyant rope use, tests were conducted at the David Taylor Naval Ship Research and Development Center (DTNSRDC), Annapolis Laboratory. The tests were designed to determine the effect of hydrostatic pressure on the buoyancy of a large-diameter synthetic-rope sample under no tensile load.

DESCRIPTION OF THE ROPE SAMPLE

The characteristics of the rope sample tested are shown in figure 1 and tabulated in table 1.

Table 1. Characteristics of the Rope Sample

Construction	Multilayered braid
Material	Multifilament polypropylene of specific gravity 0.91
Circumference	27 cm (10.5 in.) measured at a tensile load of 200 x dia.^{2} (in in.) lbf
Buoyancy	Calculated positive buoyancy of 0.477 newtons/m [0.447 newtons/m (0.3 lbf/ft) + 0.045 newtons/m (0.03 lbf/ft) - 0.015 newtons/m (0.01 lbf/ft)] in sea water over a temperature range of 0 to 20°C and under a tensile load of 200 x dia.^{2} (in in.) lbf
Minimum breaking strength	564.89 x 10^3 newtons (217 x 10^3 lbf)
Sample length	13.675 m (44.9 ft) under a tensile load of 200 x dia.^{2} (in in.) lbf
Sample weight in air	49.02 kg (108.1 lb).

Figure 1. Rope Sample Under Test

TEST APPARATUS

To measure the buoyancy of the rope in water under pressure, a commercial force transducer was modified by immersing the unit in mineral oil, as shown in figure 2. This arrangement maintained the electrical integrity of the unit in water at high hydrostatic pressures. Characteristics of the force transducer are listed in table 2.

Table 2. Characteristics of the Force Transducer

Model	Transducer incorporating an unencapsulated linear variable differential transformer (LVDT)
Range	±10 kg (±22.05 lb)
Sensitivity	±0.1 percent

The force transducer was supplied with a remote readout unit that provided for excitation and readout display of ac-operated LVDT-type transducers. The readout displayed force in kg to the nearest tenth of a kg. The entire system was calibrated in air using known weights.

The vessel in which tests were conducted was the "B" pressure tank located at the DTNSRDC Deep Ocean Pressure Facility, Annapolis, Maryland. The rope sample and force transducer were housed in the pressure vessel, as shown in figure 3. To account for the effects of pressure associated with the force transducer itself, it was necessary to calibrate the unit. The force transducer alone was placed in the pressure vessel and pressurized incrementally, going both up and down in pressure at 5-min intervals. This calibration, or "zero-shift" curve, shown in figure 4, was then used to correct the force readings obtained when the rope sample was tested under pressure.

TEST RESULTS

Following calibration of the force transducer, the rope sample and transducer were placed in the pressure vessel in the configuration shown in figure 3. The pressure vessel was flooded with water and the pressure was increased at 5-min intervals. The measured force, pressure, and water temperature were monitored over the entire pressure range. The measured force (buoyancy) versus pressure is plotted in figure 5 (the points labeled DATA).

DISCUSSION OF RESULTS

At zero pressure there is a large value of buoyant force, as shown in figure 5. At 100 $lbf/in.^2$, the buoyant force drops significantly. This

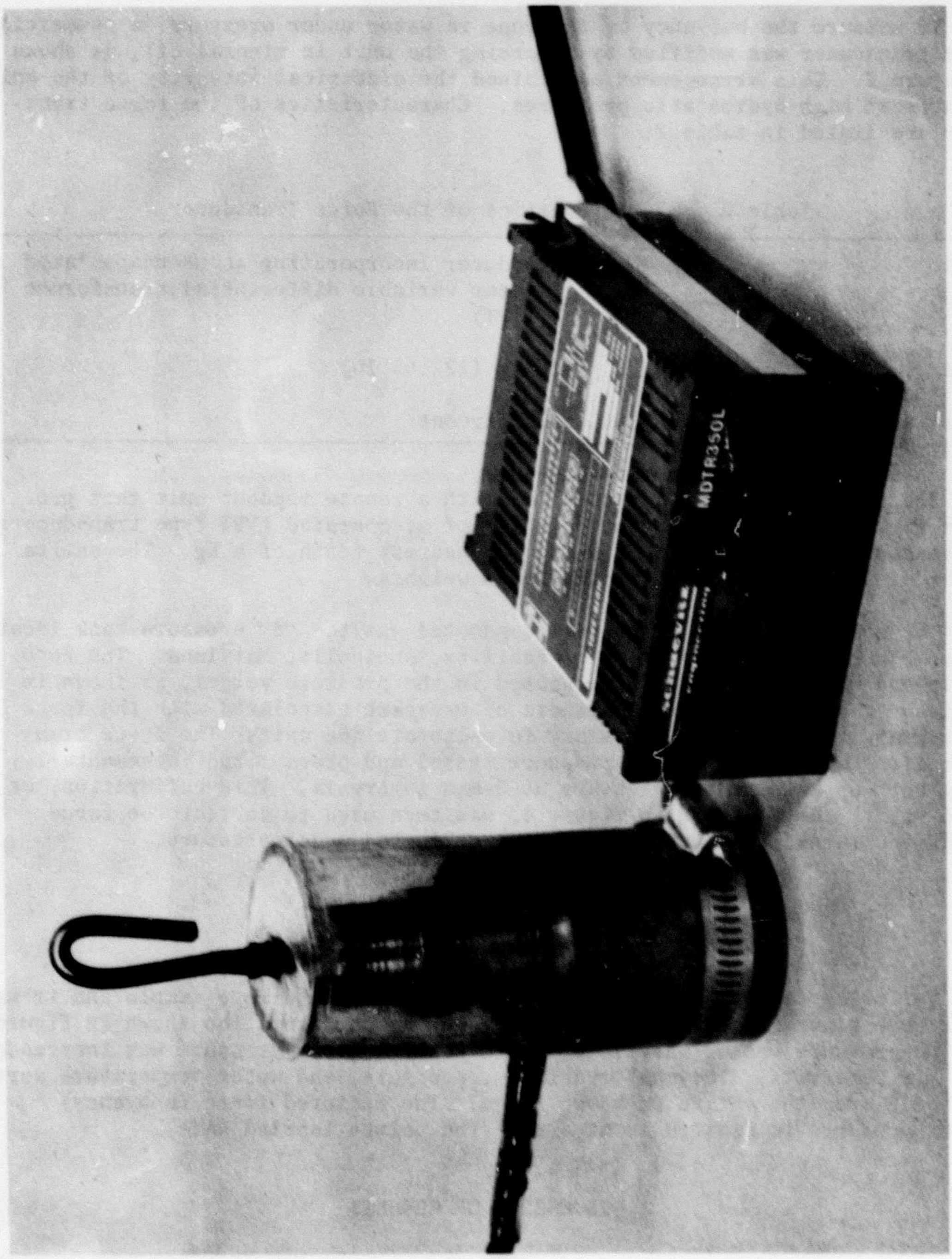

Figure 2. Modified Commercial Force Transducer

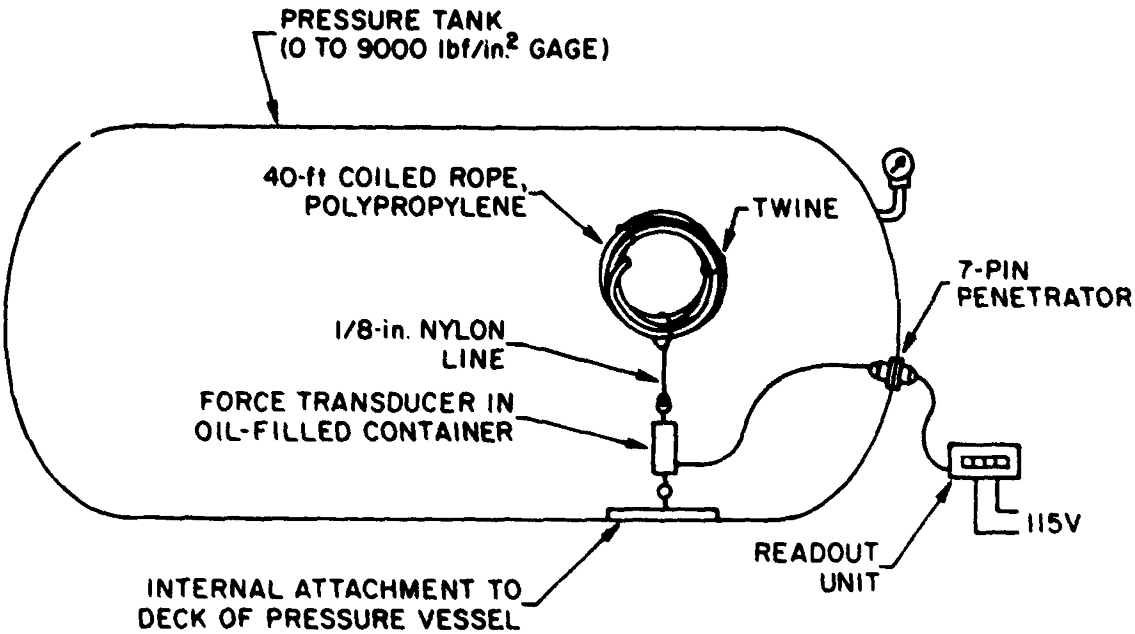

Figure 3. Physical Arrangement for Testing

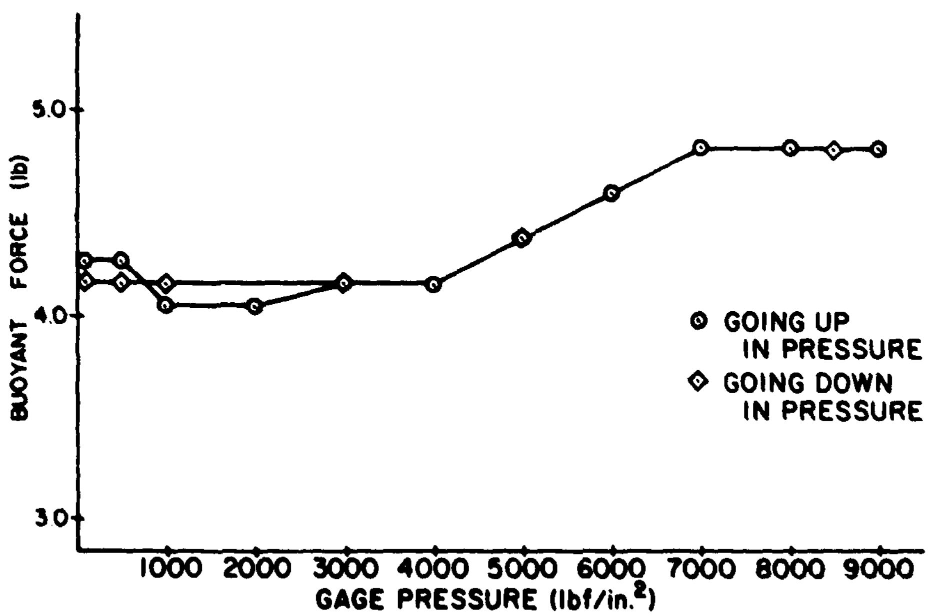

Figure 4. Buoyant Force Versus Pressure, No-Load Condition, Water Temperature at 18°C, Force Transducer Alone

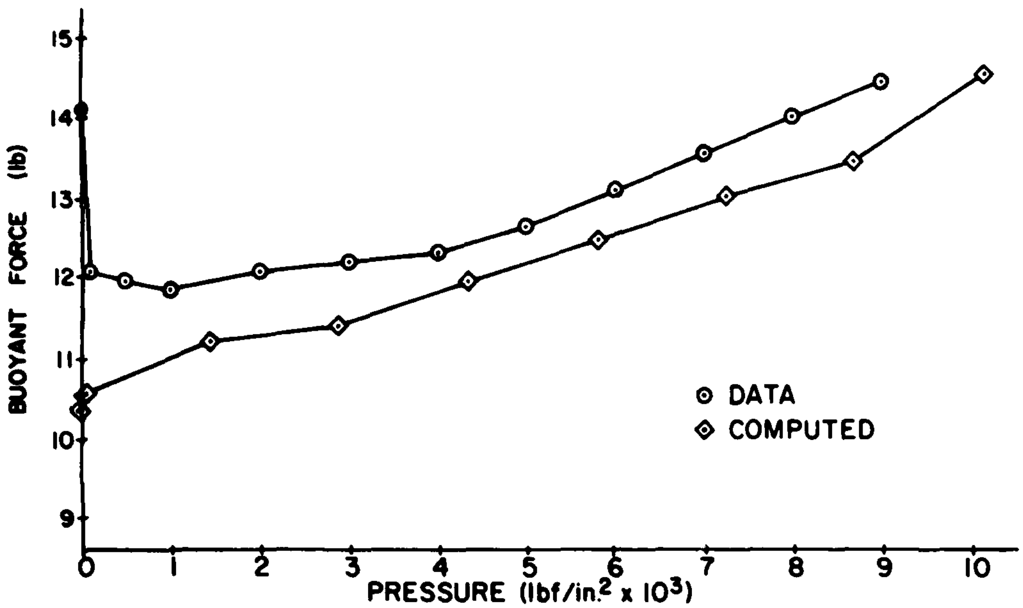

Figure 5. Buoyant Force Versus Pressure, Pure Fresh Water at Temperature of 18°C.

initially high value is attributed to air trapped in the void spaces within the braided rope. On pressurization to 100 lbf/in.^{2}, the trapped air is forced out of the voids and the buoyant force due to the material itself is realized.

With increasing pressure the measured buoyant force increases. This result can be explained by the fact that if the buoyant force is expressed by the relationship

$$B = W\left(\frac{\delta_r - \delta_w}{\delta_r}\right), \qquad (1)$$

where

B is the buoyant force in kilograms,

W is the rope air-weight in kilograms,

δ_w is the specific gravity of the water, and

δ_r is the specific gravity of the rope, then the only variables within the pressure vessel are the specific gravity of the water and the polypropylene rope.

The equation of state for fresh water based on sound-speed measurements is given by Wang and Millero.[1] Tabulated values of the specific volume of sea water (35 °/₀₀) as a function of pressure and temperature, determined experimentally, are given by Chen and Millero.[2] Using these equations and tabulated data, the increases in specific gravity due to hydrostatic pressure for fresh and salt water were computed. The results are shown plotted in figure 6 for 18°C pure water and 18°C 35 °/₀₀ sea water.

If the specific gravity of polypropylene is assumed constant, we can compute the buoyancy of the rope sample using equation (1) and figure 6. The results are plotted in figure 5 with the measured values. Although the values do not agree exactly, the general increase in buoyant force with increasing pressure can be seen for both measured and computed values. At pressures greater than 3000 lbf/in.^{2}, the trend of both values is in good agreement.

The measured and computed buoyant force values corrected for sea water (of specific gravity as shown in figure 6) are plotted in figure 7 versus pressure. In the computed case, the specific gravity of polypropylene again was assumed to be constant. In both cases there is an approximate increase of 20 percent in the buoyant force over the 100 to 9000 lbf/in.^{2} pressure interval. The measured and computed buoyant force values corrected to buoyancy per unit length in sea water as a function of pressure are shown in figure 8. Here, length is based on a tension value in pounds equal to 200 times the nominal rope diameter in inches squared.

CONCLUSIONS

The results presented in this report indicate that buoyant rope of construction similar to that tested would exhibit certain characteristics not readily apparent if measured at 1 atm. Air entrapment within the rope will give artificially high buoyant-force values if measured at 1 atm.

The compressibility effects of water and the rope material appear to be significant. If the isothermal compressibility

$$B_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right), \tag{2}$$

where

B_T is the isothermal compressibility,

V is the specific volume, and

P is pressure,

of the water (fresh or salt) changes more rapidly than that of the polypropylene, one can expect increasing buoyancy at higher ambient pressures. This

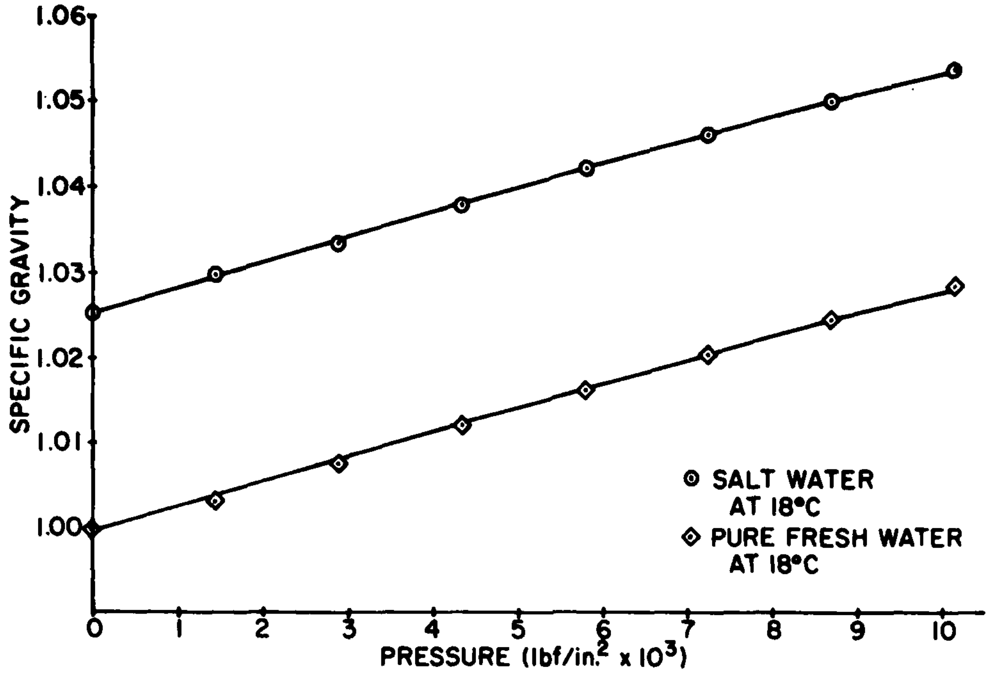

Figure 6. Specific Gravity Versus Pressure, From Millero's Data[1]

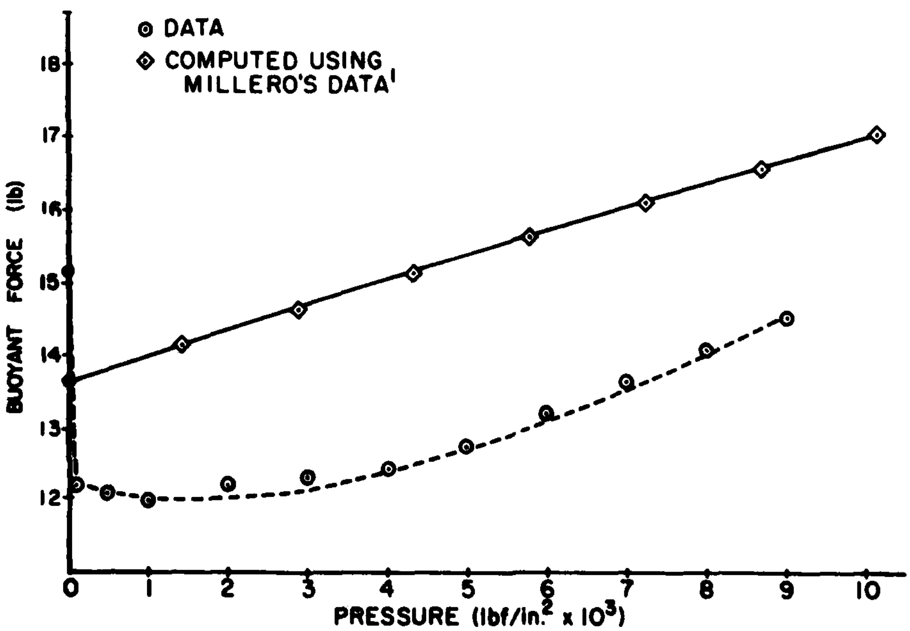

Figure 7. Buoyant Force in Sea Water Versus Pressure, Data Corrected Using Millero's Data[1] for Salt and Fresh Water

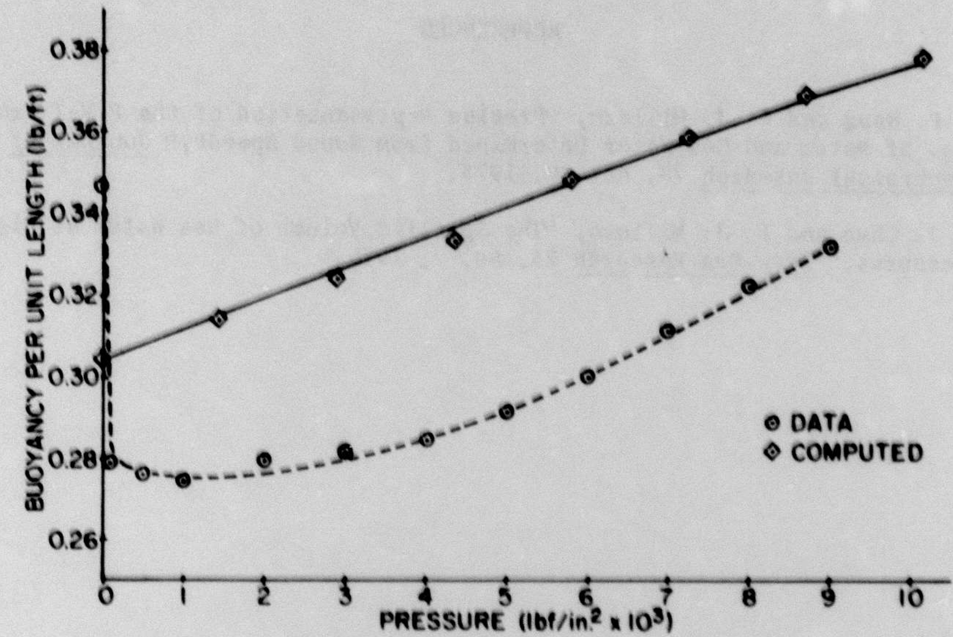

Figure 8. Buoyancy per Unit Length Versus Pressure in Sea Water (35 °/₀₀) at 18°C

effect is discussed in more detail in the appendix. Comparison of the actual data and computed plots of figure 5 shows excellent trend agreement and comparability within 10 percent above 1000 lbf/in.^{2}. This indicates that equation (1) is a useful tool in making buoyancy calculations on synthetic rope constructed of materials of low compressibility relative to fresh or sea water.

Deep-ocean cables fabricated from synthetic fibers and plastics of low compressibility (relative to fresh and/or sea water) may also exhibit different in-water weights at extreme hydrostatic pressures. For a given application, this effect may have to be taken into account.

REFERENCES

1. D. P. Wang and F. J. Millero, "Precise Representation of the P-V-T Properties of Water and Sea Water Determined from Sound Speeds," Journal of Geophysical Research 78, no. 30, 1973.

2. C. T. Chen and F. J. Millero, "The Specific Volume of Sea Water at High Pressures," Deep-Sea Research 23, no. 7, 1976.

Appendix

COMPUTATIONS

The definition of isothermal compressibility of a material is given by

$$B_T \equiv -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T , \quad \text{(A-1)}$$

where

B_T is the isothermal compressibility,

V is specific volume,

P is pressure, and

T is temperature.

As an approximation, at constant temperature

$$B_T \cong -\frac{1}{V_0}\left(\frac{V - V_0}{P - P_0}\right), \quad \text{(A-2)}$$

where

V_0 is the specific volume at pressure P_0, and

V is the specific volume at pressure P.

The specific volume at some pressure, P, is given by

$$V = V_0 - \left(B_T V_0\right)\left(P - P_0\right) . \quad \text{(A-3)}$$

The specific gravity of a material is given by

$$SG = \delta = \frac{\rho}{\rho_w} = \frac{m/v}{m_w/v_w} , \quad \text{(A-4)}$$

where

ρ is the mass density of the material,

ρ_w is the mass density of an equivalent volume of water,

m is the mass of the material,

m_w is the mass of the water, and

v is some unit volume.

Since specific volume, V, is given by

$$V = \frac{v}{m} , \tag{A-5}$$

equation (A-4) becomes

$$\delta = \frac{1/V}{1/V_w} ,$$

or

$$\delta = V_w/V . \tag{A-6}$$

The buoyancy, B, of a rope sample in water (fresh or salt) can be expressed as the difference between the weight of the rope and the weight of the water displaced by the rope. Both weights must be measured in some common medium under identical conditions of temperature and pressure. Then,

$$\begin{aligned} B &= \text{weight of rope} - \text{weight of water displaced} \\ &= \delta_r \rho_w V'_r - \delta_w \rho_w V'_w , \end{aligned} \tag{A-7}$$

where V'_r is the volume of the rope and V'_w is the volume of the displaced water.

Since $V'_r = V'_w$ at a given temperature and pressure, then

$$B = \rho_w V'_r \left(\delta_r - \delta_w\right) ,$$

or

$$B = \delta_r \rho_w V'_r \left(\frac{\delta_r - \delta_w}{\delta_r}\right) . \tag{A-8}$$

Letting the rope weight be given as

$$W_r = \delta_r \rho_w V'_r , \tag{A-9}$$

equation (A-8) becomes

$$B = W_r \frac{\left(\delta_r - \delta_w\right)}{\delta_r} = W_r\left(1 - \delta_w/\delta_r\right) . \tag{A-10}$$

The force, F, sensed by the load cell is upward, in response to the upward buoyant force of the rope, throughout all pressures measured. Then

$$F = B = W_r\left(1 - \frac{\delta_w}{\delta_r}\right). \qquad \text{(A-11)}$$

From equation (A-6),

$$\delta_w/\delta_r = \frac{V_w/V_w}{V_w/V_r} = V_r/V_w \ . \qquad \text{(A-12)}$$

Substituting values from equation (A-12) into equation (A-11) gives

$$F = W_r\left(1 - V_r/V_w\right) \ . \qquad \text{(A-13)}$$

Substituting in equation (A-13) values for the specific volumes from equations (A-3) and (A-4) gives

$$F = W_r\left[1 - \frac{v/m\left\{1 - B_{T_r}\left(P - P_0\right)\right\}}{v_w/m_w\left\{1 - B_{T_w}\left(P - P_0\right)\right\}}\right],$$

or

$$F = W_r\left[1 - \left(m_w/m\right)\left\{\frac{1 - B_{T_r}\left(P - P_0\right)}{1 - B_{T_w}\left(P - P_0\right)}\right\}\right]. \qquad \text{(A-14)}$$

Let $A = m_w/m$ and

$$C = \frac{1 - B_{T_r}\left(P - P_0\right)}{1 - B_{T_w}\left(P - P_0\right)} \qquad \text{(A-15)}$$

in equation (A-14). Then,

if $A \times C = 1$, $F = 0$, and the rope is neutrally buoyant;

if $A \times C > 1$, $F < 0$, and the rope is negatively buoyant; and

if $A \times C < 1$, $F > 0$, and the rope is positively buoyant.

For all pressures tested the rope exhibited positive buoyancy. Thus, when $P = P_0$, $C = 1$. Therefore, $A = m_w/m_r > 1$. Since m_w and m_r are constants, $A > 1$ for all pressures.

Consider F_1, which is the force at $P = P_1$, and F_2, which is the force at $P = P_2$. For all data, increasing pressure resulted in an increase in force. Therefore, for 14.7 lbf/in.^{2} $< P_1, P_2 <$ 9000 lbf/in.^{2} and $P_2 > P_1$, $F_2 > F_1 > 0$. Then, from equations (A-14) and (A-15), $F_1 = W_r\left(1 - A_1C_1\right)$ and

$F_2 = W_r(1 - A_2C_2)$; but $A_1 = A_2$, thus $W_r - W_rAC_2 > W_r - W_rAC_1$, and $C_2 > C_1$.

From equation (A-15),

$$\frac{1 - B_{T_r}(P_2 - P_0)}{1 - B_{T_w}(P_2 - P_0)} > \frac{1 - B_{T_r}(P_1 - P_0)}{1 - B_{T_w}(P_1 - P_0)} \quad . \qquad \text{(A-16)}$$

Since $P_2 > P_1$, then $B_{T_r}(P_2 - P_0) > B_{T_r}(P_1 - P_0)$, and $1 - B_{T_r}(P_2 - P_0) < 1 - B_{T_r}(P_1 - P_0)$.

If $B_{T_r} < B_{T_w}$ and $B_{T_r}, B_{T_w} > 0$, then $1 - B_{T_w}(P_2 - P_0) < 1 - B_{T_r}(P_1 - P_0)$, and the inequality in equation (A-16) is true.

Therefore, the increasing force levels measured, indicating increasing buoyancy with pressure (all trapped air considered negligible above 100 lbf/in.^{2}), imply that the compressibility of the water is greater than that of the rope with increasing pressure. Graphically this condition appears as shown in figure A-1.

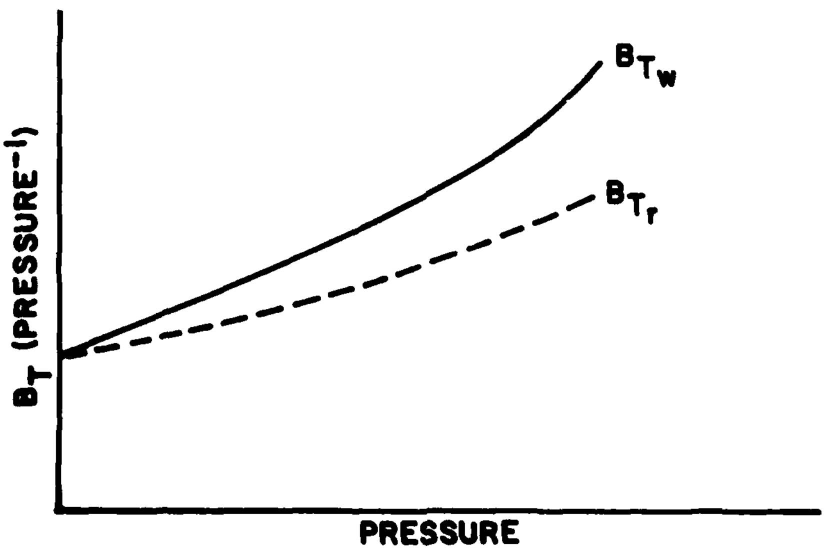

Figure A-1. Graph Showing Compressibility of Water Greater Than Compressibility of Rope With Increasing Pressure

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