

# On the Weight Adjustment of Profiling Floats

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**Abstract:** In order to park a profiling float at an appointed depth, relevant method of ballasting is examined from the view of hydrography and statics. It is shown that the weight change of float by 1 gram makes around 10 m parking depth difference, although it keeps that depth stably in the case of tropical and sub-tropical Pacific Ocean. It is pointed out that the buoyancy (i.e. bladder volume) of present APEX type float is not adequate in a certain area of western equatorial Pacific and eastern tropical Indian Ocean. Also, a method of ballasting using high pressure tank is described in detail, and calculation of ballasting weight is explained by giving an example.

**Keywords:** Argo, profiling float, parking depth, ballasting, pressure tank

## 1. Introduction

With the recent launch of the Argo project, in the near future an international effort will be made to deploy nearly 3,000 profiling floats (hereinafter referred to as “floats”) in the world’s oceans (Roemmich et al. 1999; Wilson 1999; Mizuno 2000; Saeki 2000, etc.). A float will dive to a depth of approximately 2,000 m, where it will achieve neutral buoyancy with the surrounding water. The float will drift at that depth (parking depth), and then resurface every 10 days. On the surface, it will transmit via satellite vertical profile data on water temperature and salinity collected during its ascent to the surface from the 2,000-m depth (Fig. 1). A float will repeat this cycle of observation for 4 years, and the obtained data will be exchanged in pseudo-real-time with the international community. Through the Argo project, the conditions of oceans worldwide, from the surface down to a depth of 2,000 m, will be revealed every 10 days.

Two to three types of floats are currently in use in the Argo project. All are based on a common principle for control of the ascent and descent process; the buoyancy of the float is adjusted by increasing or decreasing its volume (Fig. 2). Mineral oil is pumped into the bladder at the bottom of the float from the float inside to increase buoyancy, and is pumped back into the float inside to decrease buoyancy. Floats of this type have already been developed for deployment at relatively shallow depths (down to several hundreds of meters) (Swift and Riser 1994), and have met with success in small-scale deployment at shallow depths in specific regions in the WOCE project (Davis et al., 1992; Davis, 1999), so the technology is not totally new. However, in the Argo project, the standard parking depth is 2,000 m, and the floats must operate stably and continuously collect data for extended periods (4 years).

In this project, a large number of floats will be used. In order to deploy all of them successfully, the technical problems involved must be thoroughly examined based on oceanographic data. First and foremost, the floats must be

able to reside at their parking depth and resurface without fail to transmit the collected data. For existing floats, power consumption must be reduced to enable long-term operation. Expanding the bladder against the resistance generated by water pressure is among the operations that consume the most power. The buoyancy, or bladder volume, is therefore designed to be as small as possible, which in some regions results in a lack of sufficient buoyancy for resurfacing (Swift and Riser 2000). To optimize the buoyancy of the floats, the density of seawater at the parking depth is estimated in advance, and float ballasting is performed to provide the floats with neutral buoyancy when the bladder is at minimum volume.

In this paper, we will discuss the process of float ballasting by presenting the conditions at which the float will have neutral buoyancy from the viewpoint of statics based on the actual density distribution in the oceans, and will introduce practical methods of ballasting employed at the Japan Marine Science and Technology Center (JAMSTEC). We will also discuss the resurfacing capacity of the current model, the significance of ballasting, and the required precision for actual deployment.

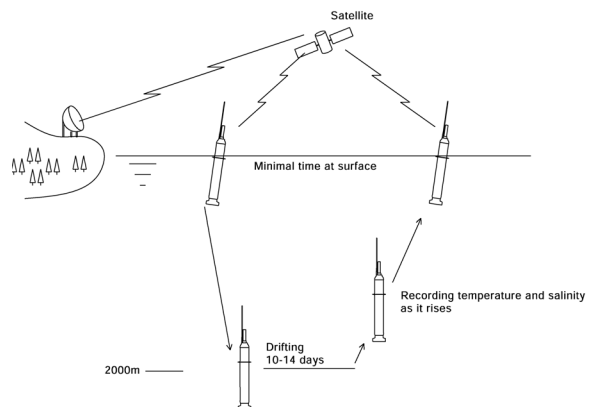


Figure 1. Schematic mission of Argo float.

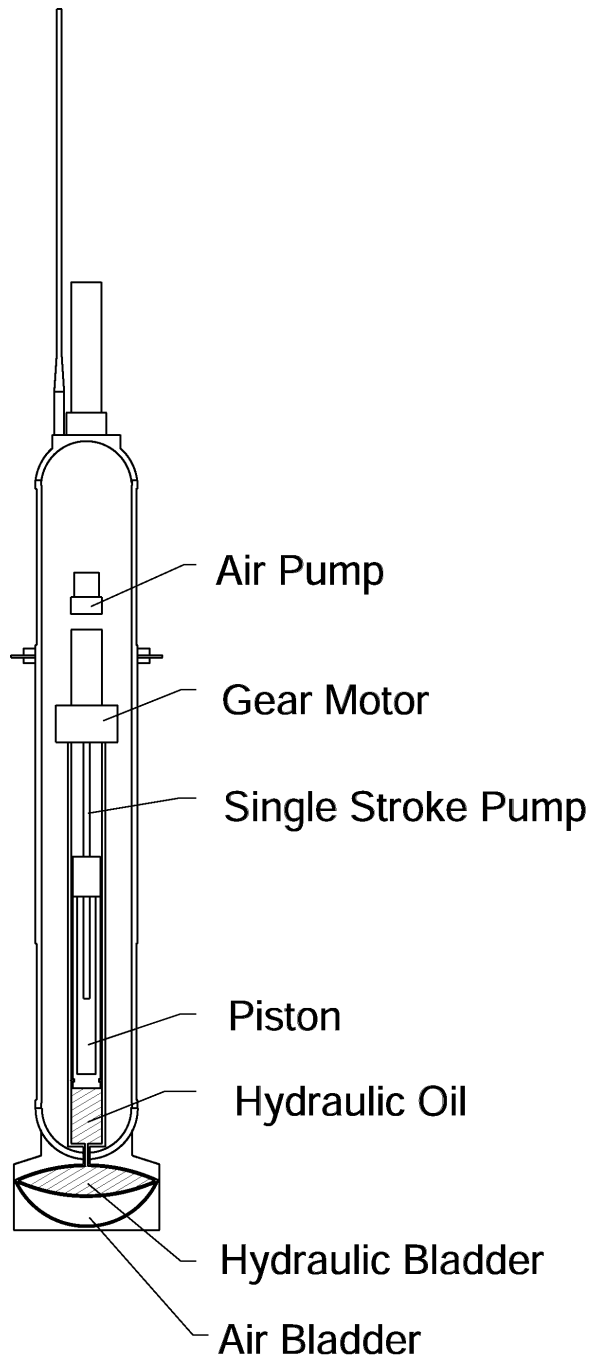


Figure 2. Sketch of profiling float (APEX type).

## 2. In situ Water Density and Temperature Distribution in the Ocean

The density of seawater is a function of its temperature, salinity, and pressure. Figure 3 shows a vertical cross-section of the in situ seawater density along the 130°E meridian. It can be seen from this figure that the density at a depth of 2,000 m in the North Pacific is approximately 1037 kg/m<sup>3</sup> (the vertical axis represents the pressure in units of decibars, and these values are nearly equivalent to the depth in meters). This implies that, once a float reaches neutral buoyancy at this depth, the drifting float will be able to maintain a nearly constant parking depth as long as the buoyancy of the float itself remains stable.

The vertical profile of the average in situ density in this region is also presented at the right-hand side of the figure. At this depth, the profile is almost linear, and the rate of change in the in situ density is nearly constant (at 0.005 kg/m<sup>3</sup> per meter). If for simplicity's sake the float volume is assumed to be 20 liters, this vertical density slope indicates that a change in float weight of 1 gram will change the float density by 0.05 kg/m<sup>3</sup>, which translates into a 10-m change in parking depth. A change in float volume of 1 cm<sup>3</sup> will also produce similar results. This indicates that extremely precise control of the float weight and volume is necessary to achieve a margin of error in parking depth of less than 10 m.

On the other hand, a float must maintain a constant density once it has achieved neutral buoyancy at the parking depth. The float body is made of aluminum and is compressed by water pressure, although its compression is less than that of the seawater. Therefore, even if a float deviates slightly from its parking depth due to some perturbation of the seawater, the extent of its compression (expansion) due to the increase (decrease) in water pressure is less than that of the surrounding seawater. Since the float will be lighter (heavier) than the surrounding seawater as a result, it will return to its original parking depth. In this way, a float will be able to drift stably at its parking depth.

The metal body causes the float volume to change when the temperature of the surrounding water changes. Figure 4 shows the distribution of the annual mean water temperature in the Pacific Ocean at a depth of 2,000 m. The overall spatial variations are small, particularly in the North Pacific, where the water temperature is nearly constant at 2°C in all regions, and the local variations are mostly within the range of ±0.2°C. According to the World Ocean Atlas 1998 (NOAA, 1998), the temporal variations in water temperature are even smaller and, in most regions, the standard deviation is smaller than ±0.05°C. The change in float volume caused by spatial variations in water temperature (0.2°C), calculated from the physical properties of the body material (aluminum) produces almost no change in parking depth.

## 3. Balance of Forces at Parking Depth

In order for the float to reach neutral buoyancy at the parking depth, the gravity acting on the float must be equal to the buoyancy of the float. This relationship can be expressed by the following equation:

$$M_n g = \rho(s, t, p) V(t, p) g \dots (1)$$

The left-hand side of the equation represents the effect of gravity, and the right-hand side represents the buoyancy. Here,  $M_n$  is the float mass in the state of neutral buoyancy,  $g$  is the acceleration of gravity, and  $s$ ,  $t$ , and  $p$  represent salinity, temperature, and pressure, respectively.  $\rho$  is the in situ density of the seawater at parking depth.  $V$  is the float volume at parking depth, which changes with temperature and pressure, but this change is dependent on the physical properties of the float body.

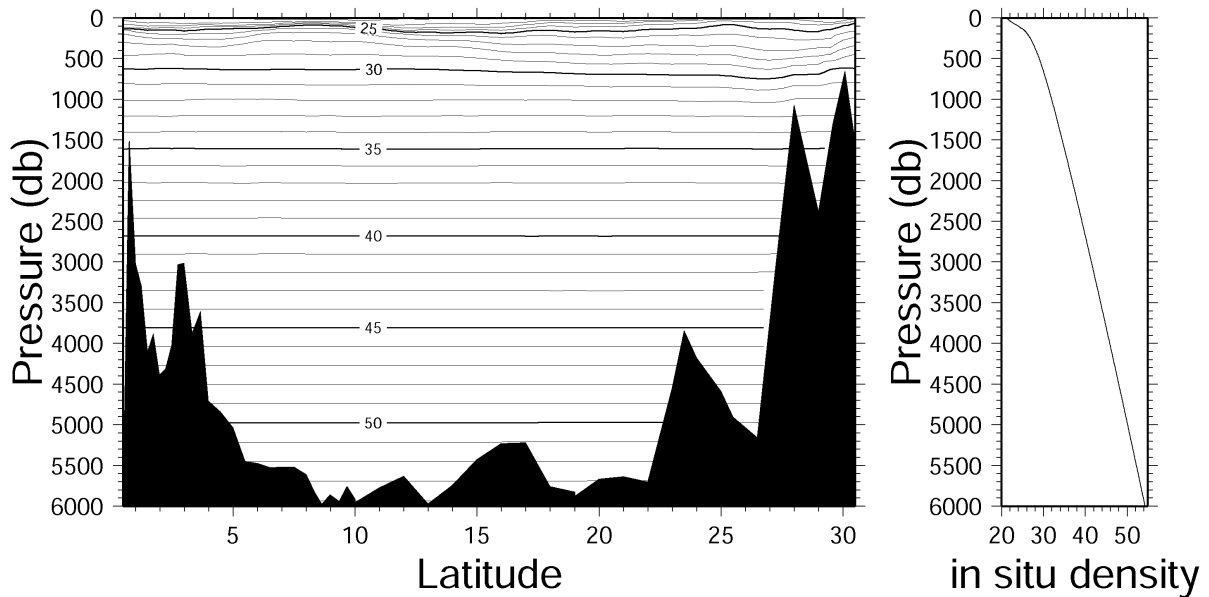


Figure 3. Vertical section of in-situ density along 130°E meridian.

As previously mentioned, the in situ density  $\rho$  is stable at a depth of 2,000 m in the North Pacific, and can be predicted with significantly good precision prior to deployment. In addition,  $M_n$  can be adjusted freely by placing weights (ballast) inside the float. Ballasting is the operation of adjusting the float weight so that the float reaches neutral buoyancy at the specified depth. The remaining problem is how to determine the float volume  $V(t,p)$  at the parking depth. The float volume is calculated using the following equation:

$$V(t,p) = V_0[(1 - \gamma p) + \alpha(t_0 - t)] \dots(2)$$

Here,  $\alpha$  is the coefficient of thermal expansion of the float volume, and  $\gamma$  is the compressibility of the float.  $V_0$  is the float volume at room temperature (an appropriate standard temperature is to be selected) and 1 atm.  $\alpha$  is calculated from the coefficient of linear expansion of the body material (the coefficient of thermal expansion is 3 times the coefficient of linear expansion). Therefore, if the unknown parameters,  $V_0$  and  $\gamma$  can be determined by some method, it will be possible to calculate the float weight in the state of neutral buoyancy at the parking depth from equation (1). Normally,  $V_0$  exceeds 20 liters, and it is extremely difficult to measure the volume with an error of less than 1 cm<sup>3</sup>. Therefore,  $V_0$  could be determined through the experiment using pressure tanks described in the following section.

#### 4. Ballasting Experiments Using Pressure Tanks

The pressure-tank system is shown schematically in Fig. 5. The system includes a video camera and a stand inside the tank and a video monitor outside the tank. The stand serves as a platform for attachment of the camera and as a protective frame for the float. The float is placed inside this

frame with a chain connected to the bottom of the float (Photo 1). The tank must also contain a thermometer and a pressure gauge. If the tank is not equipped with these instruments, a CTD will be placed inside the tank.

In the experiment, the pressure tank is filled with fresh water (normal tap water) and sealed shut, and the pressure is then gradually increased. At first, the float rests on the base of the stand. As the pressure increases, the float volume is compressed, but the surrounding water is also compressed, so the density of the water increases. As the compressibility of the water is higher than that of the float, the buoyancy of the float gradually increases, and the float begins to rise when the buoyancy exceeds its weight. This excess buoyancy lifts the chain attached to the bottom of the float and the excess buoyancy is balanced. If the length of the lifted chain is measured by reading the marks on the side of the float (normally at 2-cm intervals) on the video monitor, the weight of the lifted chain, or the excess buoyancy, can be calculated.

At the beginning of the experiment, the float must rest on the bottom, so ring weights are placed on the float antenna prior to the experiment (Photo 2), and the float is adjusted to be slightly heavier than neutral. The ring weight is adjusted so that the float will begin to rise with only a slight increase in pressure and so that the marks on the float sides to be read will remain within the field of view of the monitor, even under maximum pressure. This adjustment of the weight prior to the experiment is referred to as “rough ballasting,” and is performed based on past experimental results; or if it is being performed for the first time, by actually placing the float in water and increasing or decreasing the number of rings. In addition, an attachment must be fixed to the float bottom for the chain (Photo 3). The maximum total weight of the weight, attachment, and

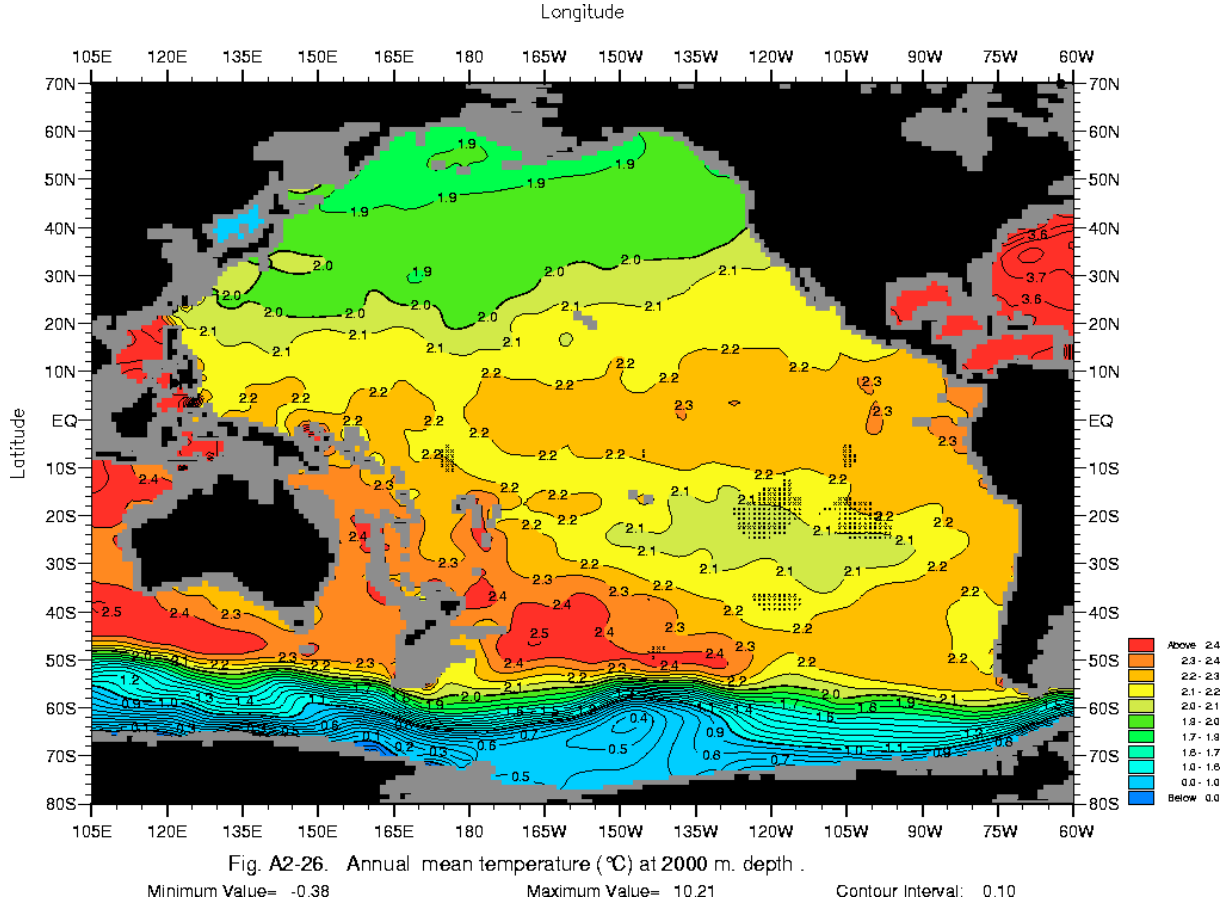


Figure 4. Annual mean temperature (°C) at 2000m depth. Contour interval is 0.1°C (after WOA98)

chain is set at 200 g (approximate volume: 25 cm<sup>3</sup>), to allow its effect on the change in float weight in the water caused by the change in water density during pressurization to be ignored.

If the float lifts the chain by length  $h$  at a certain pressure  $p$  and comes to rest, the balance of forces acting on the float can be expressed by the following equation (the acceleration of gravity is omitted for simplicity's sake):

$$M_f + m_c h(t, p) + m_w = \rho(0, t, p) V_0 [1 - \gamma p + \alpha(t - t_0)] \dots (3)$$

Here,  $m_c$  is the weight of the chain per unit length in water, and  $m_w$  is the total weight in water of the ring weights and the attachment for rough ballasting. In equation (3),  $M_f$ ,  $m_c$ ,  $m_w$ , and  $\alpha$  are known constants,  $t$  can be measured and, in the experiment, pressure ( $p$ ) is applied to obtain  $h$ . In addition,  $\rho$  can be calculated from  $p$  and  $t$ . Therefore, the remaining unknowns in equation (3) are the 2 constants  $V_0$  and  $\gamma$ .  $t$  can basically be considered constant, so  $m_c h$  becomes a function only of pressure. Therefore, the sum of the second and third term on the left-hand side ( $m_c h(t, p) + m_w$ ) can be written as  $M(p)$ . If the temperature inside the tank is set at the standard water temperature ( $t = t_0$ ), then equation (3) becomes

$$M(p) = \rho(p) V_0 (1 - \gamma p) - M_f \dots (4)$$

If the compressibility of water (the inverse of the coeffi-

cient of thermal expansion) is represented by  $\kappa(p)$ , this equation can be approximated as follows, and the plot for this equation will show that the ballast weight increases almost linearly with the pressure (see Appendix A):

$$M(p) = \rho(0) V_0 (\kappa(p) - \gamma p) + (\rho(0) V_0 - M_f) \dots (5)$$

If  $M(p)$  is measured at two different pressures in equation (4), simultaneous equations with  $V_0$  and  $\gamma$  as the unknowns will be obtained; by solving the equations, the function for  $M(p)$  can be determined. However, since  $M(p)$  will contain measurement errors, the problem of precision remains in the estimation of  $M(p)$  by this method. Therefore, many measurements were made of  $M(p)$  at different pressures to produce a linear regression equation for  $M(p)$  as a function of  $p$  ( $M(p) = Ap + B$ ), in order to estimate  $M(p)$ .

The theoretical ballasting curve obtained from equation (4) has its intercept at  $M(0) = \rho(0) V_0 - M_f$ . This intercept corresponds to intercept B of the regression line calculated from the results of measurement, so the two are approximately equal ( $B = \rho(0) V_0 - M_f$ ). It should therefore be possible to obtain the approximate value of  $V_0$ .

The float volume at parking depth ( $V_0(1 - \gamma p)$ ) can easily be calculated from equation (4). Adding the change in volume resulting from thermal expansion due to the in situ

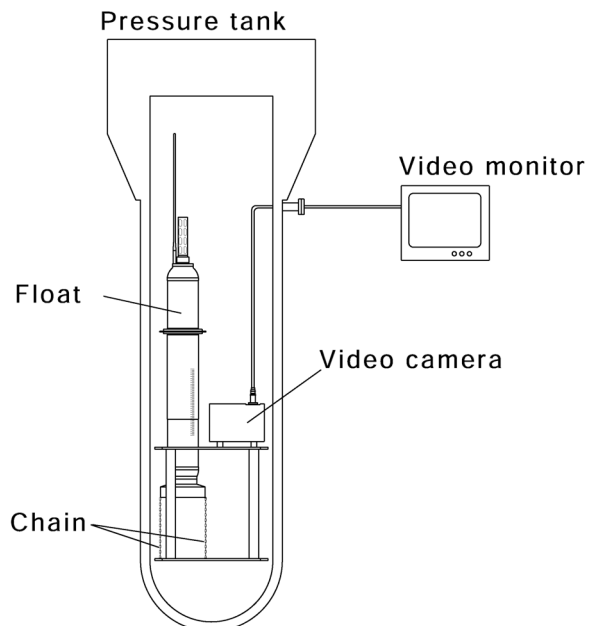


Figure 5. Pressure tank system used in this ballasting experiment.

temperature derived from equation (2) makes it possible to calculate the total in situ volume of the float. The product of this volume and the seawater density will be equal to the total weight of the float in the state of neutral buoyancy (see equation (1)). The total weight of the float should be adjusted to this value through the addition of ballast.

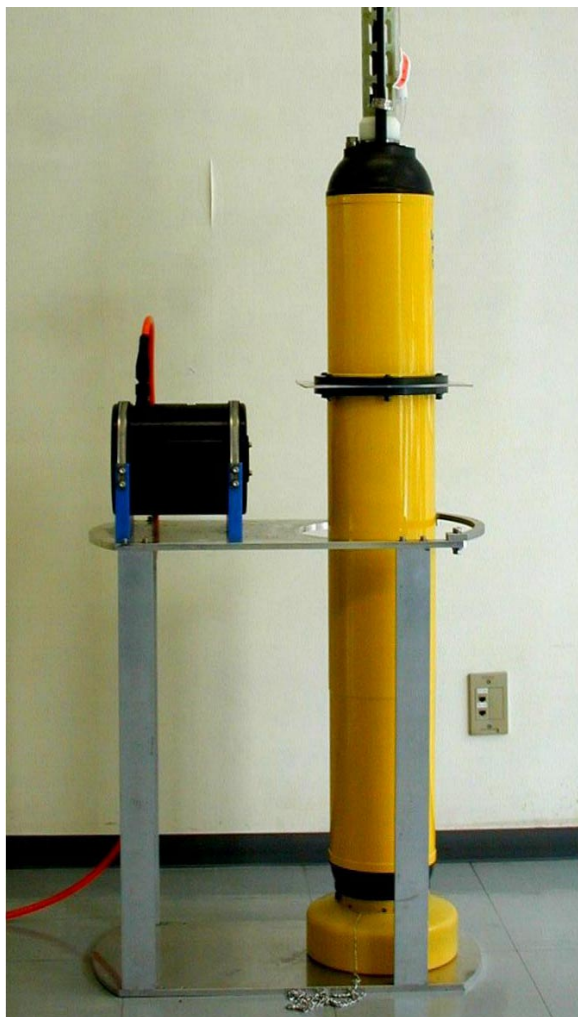


Photo1. Float and video camera with stand.



Photo2. Weights for rough ballasting (rings put on the antenna).



Photo3. Chain with attachment to the float.

## 5. Example of a Ballasting Experiment

Here, we will present an example of a ballasting experiment conducted at JAMSTEC. The float used in this experiment is the APEX-SBE model manufactured by Webb Research Corporation (SN.255). To monitor the temperature and pressure during the experiment, a SeaBird CTD sensor (SBE9plus) was placed inside the pressure tank. The precision of temperature and pressure measurements is 0.001°C and 0.9 db, respectively.

After the float was placed inside the tank, the tank was sealed shut and pressurized from zero pressure to approximately 2,000 db. Then, the pressure was gradually decreased, and the length of the lifted chain was measured under various pressure conditions. The pressure was then increased again to take measurements, which were obtained for a total of 11 points (Table 1). From this data set, the following linear regression equation is obtained:

$$M(p) [g] = 0.061099[g/db]p[db] - 81.79[g] \dots(6)$$

This equation is referred to as the “ballasting curve.” Figure 6 shows the experimental results and the linear regression curve. The slope of this line represents the increase in buoyancy of the float when the pressure increases by 1 db, and the Y intercept represents the ballast weight that is necessary when the float is at zero pressure. In this case, the weight exceeds the buoyancy by 81.79 g at 1 atm, which indicates that the float had been at rest on the base of the stand.

Table 2 shows the details of the items used in the experiment. First, the pressure at parking depth (1) is set arbitrarily, and estimated values are assigned to (2) and (3). Items (4)-(6) and (9) are measured values. Item (7) is known; in this case, the material of the Webb APEX-model float is aluminum (AL-6061) (Webb Research Co., 1999).

Therefore, the coefficient of linear expansion ( $2.3 \times 10^{-5}/^{\circ}\text{C}$ : Dexter 1979) multiplied by a factor of 3 was used as the coefficient of thermal expansion of the float.

Item (10) can then be determined from calculation or experimentally. Finally, item (17), the ballast weight  $M_b$  to be added to the float, is determined. The details of these calculations are shown in the program list in Appendix C.

The compressibility of the float has not been calculated directly, but in the process of calculating the float volume  $V_0(1 - \gamma p)$  under pressure for item (13), the value including the volume and compressibility is obtained. Therefore, it is not necessary to explicitly calculate the compressibility itself. However, when calculated, the compressibility is found to be  $\gamma = 2.230 \times 10^{-6}/\text{db}$ . This value is approximately half that of seawater (see Table A1 in Appendix A).

The theoretical ballasting curve can be approximated fairly well by equation (5) in the previous section. Since in equation (5),  $\rho(0)V_0(\kappa(p) - \gamma)$  is nearly constant, the equation can be approximated to a linear equation with this value as the slope. This value, calculated using the average value of  $\kappa(p)$ , is 0.06184, and it can be seen that this value

Table 1. Ballasting Experiment data

Measurement Number	Pressure [dbar]	Rising length [cm]	Chain Weight [g]	Total ballast [g]
1	1920.1	38.80	31.35	35.89
2	1818.4	31.20	25.21	29.55
3	1727.7	24.20	19.55	23.89
4	1623.4	16.20	13.09	17.43
5	1528.6	9.40	7.80	11.94
6	1427.5	1.40	1.13	5.47
7	1477.2	4.80	3.88	8.22
8	1578.5	12.80	10.18	14.52
9	1675.8	19.80	16.00	20.34
10	1773.4	27.40	22.14	26.48
11	1871.8	34.60	27.96	32.30

\*Chain Weight : Calculated from rising length of the chain  
\*Total Ballast: Weight of ( Chain + Ring + Attachment )

is in a relatively good agreement with the above regression curve.

## 6. Conditions for Resurfacing

As discussed thus far, a method has been established for determining the float weight that will achieve neutral buoyancy at the preferred depth. However, the other condition a float must satisfy is that it is able to resurface in order to transmit the observation data via satellite. For the float to rise to the surface, the bladder must be inflated in order to decrease the density of the float to less than that of the surface seawater. In other words, the float should satisfy the following condition:

$$\rho(V_s + \delta V) > \rho' V(t,p) \dots (7)$$

where  $V_s$  is the float volume at the surface,  $\delta V$  is the volume of expansion of the bladder,  $\rho$  is the density of seawater,  $V(t,p)$  is the float volume at parking depth, and  $\rho'$  is the density of seawater at parking depth. The standard temperature is set as that at the surface ( $V_s = V_0$ ).

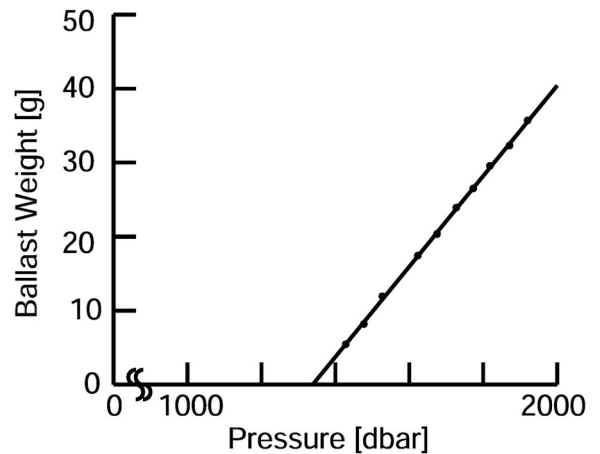


Figure 6. An example of ballasting curve obtained by the experiment

Table 2. Specification of ballast weight calculation

(item)	(symbol)	(value)	(remarks)
①pressure at parking depth	p	2000 [dbar]	arbitrary
②in-situ temperature at parking depth	t	2.0 [°C]	estimated
③in-situ density at parking depth	$\rho(s, t, p)$	1.03687 [g/cm <sup>3</sup> ]	estimated
④initial weight of float	$M_f$	25050.5 [g]	measured
⑤weight of chain per unit length (in water)	$m_c$	0.808 [g/cm <sup>3</sup> ]	measured
⑥weight of attached ring weight(in water)	$m_w$	4.34 [g]	measured
⑦coefficient of thermal expansion of float	$\alpha$	$6.90 \times 10^{-5}$ [/°C]	property of alminum
⑧tank water pressure	p	2000 [dbar]	same as ①
⑨tank water temperature	$t_0$	9.20 [°C]	measured
⑩tank water density	$\rho(0, t_0, p)$	1.00916 [g/cm <sup>3</sup> ]	equation of state
⑪added weitht to the float	$m_c h(t, p) + m_w$	40.4 [g]	ballasting curve
⑫total weitht of the float	$M_t$	25090.9 [g]	$M_f + m_c h(p) + m_w$
⑬float volume in the tank	$V_0 [1 - \gamma p]$	24863.1 [cm <sup>3</sup> ]	$M_t / \rho(0, t_0, p)$
⑭float volume in air pressure	$V_0$	24974.5 [cm <sup>3</sup> ]	ballasting curve
⑮float volume at parking depth	$V_p$	24850.7 [cm <sup>3</sup> ]	$V_0 [1 - \gamma p + \alpha(t - t_0)]$
⑯float weight at parking depth	$M_n$	25767.1 [g]	$\rho(s, t, p) V_p$
⑰ballast weight	$M_b$	716.6 [g]	$M_n - M_f$

Substituting equation (2) for  $V(t, p)$  makes the above inequality

$$\delta V > V_s(\rho'/\rho)\{(1 - \rho'/\rho) - \gamma p + \alpha(t_p - t_s)\} \dots(8)$$

Here,  $t_p$  and  $t_s$  are the water temperatures at the parking depth and at the surface, respectively. If both sides of the above inequality are equal, then the float reaches neutral buoyancy quite close to the surface. In practice, the float will require sufficient buoyancy to raise the antenna completely into the air; however, this is achieved by a separate maneuver near the surface, in which air is pumped into the air bladder to inflate it, so there is no need to take this into consideration in the above calculations.

On the right-hand side of the above inequality,  $p$  is the specified parking depth (2,000 db), and the temperature ( $t_p$ ) and in situ density ( $\rho$ ) at the parking depth can be estimated fairly precisely, as previously mentioned. Furthermore,  $\alpha$  is known, and  $\gamma$  can be obtained from the ballasting experiment described in the previous section. If  $\delta V$  the on the left-hand side is assumed to be constant, whether a float can reach the surface will depend solely on whether inequality (8) holds true, which can be judged if the density and the temperature of the seawater at the surface are available.

Here, we will estimate the values of the terms in the bracket on the right-hand side of inequality (8). As our focus is on regions in which there is a large density difference between the parking depth and the surface, we will consider a case in the tropical/subtropical region. The difference in density ( $1 - \rho'/\rho$ ) is approximately  $20 \times 10^{-3}$ , the

effect of compression of the float ( $-\gamma p$ ) is  $-5 \times 10^{-3}$ , and the effect of the change in temperature ( $\alpha(t_p - t_s)$ ): the effect of the change of 20°C is  $-1$  to  $-2 \times 10^{-3}$ ; the effect of the difference in density is larger than the others, but all are on the same order.

Although the spatial and temporal variations in the density

and temperature of surface seawater are large, the standard deviations were calculated for each region from past observation data. Based on the assumption that the variations have a constant correlation (in this case, -0.75) and are random variables that follow a normal distribution, the probability of the float resurfacing was calculated. The calculations were made for the Webb APEX-model floats (bladder oil volume: 260 cm<sup>3</sup>), and the probabilities of resurfacing were calculated for each region within a grid of 5° long. x 5° lat. using historical data (WOA98) (Fig. 7). However, since the bladder oil is never totally used, as will be explained in the following section, it was assumed that 80% of the available bladder oil was used for resurfacing. It can be seen from the figure that there is a high probability of the floats not resurfacing in the warm pools of the tropical Pacific and the eastern Indian Ocean. In these regions, it is not possible to conduct observations with certainty down to a depth of 2,000 m using existing floats; floats with greater buoyancy must be developed.

## 7. Discussions

As the ballasting experiment involves various factors that result in measurement errors, the ballast weights determined in this experiment contain small errors. In addition, small errors exist between the actual in situ density and temperature of seawater and the assumed values. Therefore, it will be necessary for a float to be equipped with a mechanism to automatically correct for these small errors. A float is programmed to measure the pressure as it descends following deployment, and when it nears the specified parking depth, to stop at the preset depth by making fine adjustments to the amount of oil pumped into the bladder. (This is performed only during the first descent. After the second descent, the same amount of oil

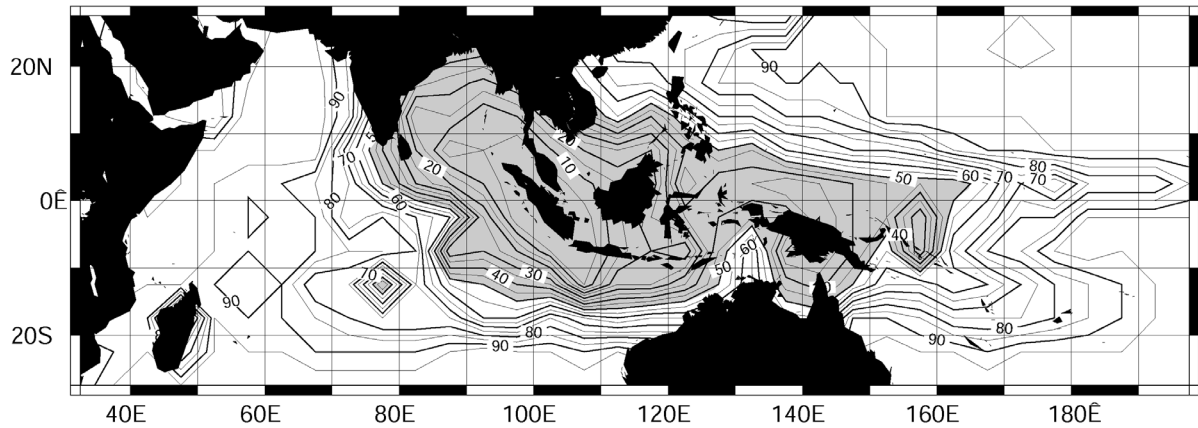


Figure 7. Annual mean probability of surfacing from 2000db for floats with 260cm<sup>3</sup> bladder oil volume (with a safety margin of 20%).

as in the first descent is pumped into the bladder.) To allow it to make this fine adjustment, the bladder should not be completely compressed at the parking depth and should have some excess capacity. Therefore, it is not always possible to utilize the total bladder oil volume.

Existing floats do not have sufficient buoyancy to resurface in some regions, as previously mentioned, so it is necessary to perform ballasting with high precision in order to achieve maximum buoyancy. Particularly in the tropical and subtropical regions of the Pacific Ocean, as well as in the eastern Indian Ocean, ballasting is extremely important.

### 7.1 Examination of the Precision of the Ballasting Experiment

To determine  $M(p)$  in the ballasting curve, the only item necessary to be measured is the length of the lifted chain. This length is converted into the weight of the chain and added to the constant weight of the ring weights and the attachment in order to obtain the total lifted weight. The chain, ring weights, and attachments are all made of stainless steel, their weights in air and in water are measured, and their densities calculated from these measurements are used to confirm their material composition. The weight measurements can be made with a precision of 0.02 g using an electronic balance calibrated with standard weights.

The precision of the weight of the lifted chain depends on the precision (0.2 cm) of the reading of the marks on the side of the float, which are at 2-cm intervals. The weight of the chain per unit length is 0.8 g/cm, so the measurement error is 0.16 g. Since the weight of the ring weights and the attachment is measured with a precision of 0.02 g, the measurement error for the total lifted weight is approximately 0.16 g. However, measurement error of approximately 1 db also exists for  $p$ . The effect of these errors on  $M(p)$  is proportional to the slope of the regression line, which in this experiment was 0.06 g. Therefore, the measurement error for  $M(p)$  propagating from the two errors is the square root of the sum of their squares, and is estimated at 0.17 g.

Each of the measured values of  $M(p)$  contains the above error and certain other errors caused by various factors.

Therefore, a regression line is drawn for the experimental values by the least-squares method in order to determine  $M(p)$ . The predictive error can be estimated based on the extent of the difference between the value from this regression line and the measured values. In this case, the deviations between the individual values measured and the fitting line ( $\varepsilon_i = y_i - Y_i$ , where  $y_i$  is the  $i$ th measured value and  $Y_i$  is the predicted value from the fitting line) are calculated,

and the standard deviation ( $\sqrt{\sum \varepsilon_i^2 / (n - 2)}$ ) serves as the predictive error. Here,  $n$  is the number of experiments. The denominator is  $(n-2)$  because the degree of freedom was reduced by 2 when the slope and intercept were determined from the experimental values. The predictive error in this experiment was 0.24 [g]. When  $S_e$  is the predictive error, the confidence interval for the predicted value  $y$  at pressure  $X$  can be calculated using the following equation (Tanaka and Wakimoto, 1983):

$$Y - t_\alpha \sqrt{\{1 + 1/n + (X - X_{mean})^2 / nS_{xx}\}} S_e < y < Y + t_\alpha \sqrt{\{1 + 1/n + (X - X_{mean})^2 / nS_{xx}\}} S_e$$

$Y$  is the value on the regression line for pressure  $X$ , and  $X_{mean}$  and  $S_{xx}$  are the mean and variance (the sum of the squared deviation divided by  $n$ ) of  $X$  for this experiment, respectively. For the 95% confidence limit,  $t_\alpha = 2.262$ , as the degree of freedom is 9, so the 95% confidence interval for the regression line at a pressure of 2,000 db is  $40.41 \pm 0.67$  [g]. This satisfies the required precision of 1 g.

It should be noted here that, in the experiments, the allowable range of the standard deviation for the difference between the values predicted from the regression line and the values obtained in the experiment was set at less than 0.8 g. In this example, the standard deviation was well within the allowable range. If the standard deviation falls out of the allowable range, the experiment is performed again.

### 7.2 Estimated Error in Ballast Weight

In ballasting, only the weight to be added to the float ( $M_b$ ) need be known. In Table 2 of Section 5, successive calculation is performed, but the error in ballast weight can

be estimated more easily if the calculations are performed collectively. From Table 2,

$$M_b = M_n - M_f = \rho(s,t,p)V_0\{1 - \gamma + \alpha(t - t_0)\} - M_f.$$

By substituting  $V_0(1 - \gamma) = (M(p) + M_f)/\rho(0,t_0,p)$  in this equation, we obtain

$$M_b = \rho'(M(p) + M_f)/\rho + \rho'V_0\alpha(t - t_0) - M_f$$

when, for simplicity's sake,

$$\rho = \rho(0,t_0,p), \rho' = \rho(s,t,p).$$

Then, this can be written as

$$M_b = M(p)\rho'/\rho + \rho'V_0\alpha(t - t_0) + M_f(\rho' - \rho)/\rho. \dots (9)$$

Here, since  $\rho'$  is up to 1,  $\rho$  is up to 1,  $\rho'/\rho$  is up to 1,  $(\rho' - \rho)/\rho$  is up to 0.03, and  $\alpha(t - t_0)$  is up to 0.0014 (at a water temperature of 20°C), the effect of error can be estimated for each item on  $M_b$ .

It is evident from the first term that the measurement error in  $M(p)$  directly affects the error of  $M_b$ . On the other hand, since the value of  $\alpha(t - t_0)$  is small, the second term will only affect the error in  $M_b$  by 0.014 g, even when the error in  $V_0$  is 10 cm<sup>3</sup>. The third term only produces an error in  $M_b$  of 0.3 g for an error in  $M_f$  of 10 g, and does not significantly affect the error in  $M_b$ . Therefore, to determine  $M_b$  with high precision, the precision of the ballasting curve must be improved.

### 7.3 Effects of Changes in Tank Water Temperature and Air Bubbles

In the pressure tank experiment, the water temperature inside the tank should increase with an increase in pressure due to adiabatic compression. It is estimated that the temperature will rise by 0.14°C when a pressure of 2,000 db is applied to the tank. This increase in temperature will cause a decrease in the density of 0.000018 g/cm<sup>3</sup>. However, this effect is ignored in the experiments for the reasons specified below.

Since the float volume [cm<sup>3</sup>] and weight [g] are both approximately 25,000, if  $\rho$  in equation (9) is affected, the third term will increase by 0.44 g. The temperature increase will also affect the ballasting curve. Due to the decrease in density caused by the increase in temperature at the maximum pressure of 2,000 db, the float volume will increase (by 0.24 cm<sup>3</sup>), making the net result a decrease in float buoyancy of 0.20 g. This in turn will cause a decrease in the weight lifted in the ballasting curve. However, since the effect of adiabatic compression is greatest at 2,000 db, and since the temperature increase is small at lower pressures, the effect on the predictive error of the ballasting curve is considered to be small. The estimated error in  $M_b$  is affected primarily by the third term in equation (9), but the effect is negligible.

Although the effect of adiabatic changes on ballasting is relatively small, in the actual experiment it may create a thermocline inside the tank or cause temporal changes in temperature. As the temperature inside the tanks is assumed to be within the range of 10-20°C, the effect of a 1°C rise in temperature can be estimated in a similar manner. Such a rise will cause a decrease in density of 0.0001 g/cm<sup>3</sup>, which in turn will cause an increase of 2.5 g in the third term in equation (9), and the ballasting curve will fall overall by approximately 0.8 g. The resulting error in  $M_b$  caused by a temperature increase of 1°C is approximately 1.7 g, which exceeds the allowable range. Therefore, the water temperature inside the tank must be strictly controlled during the experiment to maintain a uniform distribution and stable temperature. The test tank used in this experiment is filled with tap water that has been stored in a reservoir tank and left overnight prior to pressurization. Several buoyancy experiments were conducted in autumn and winter, and the water temperature even during these cold periods was relatively stable.

When a float is placed inside the tank, air bubbles inevitably form on the surface of the float. The air bubbles increase the float volume and contribute to the error in equation (4). However, as the volume of air bubbles is inversely proportional to the pressure, the error due to air bubbles decreases rapidly with an increase in pressure. In the experiment, pressure is applied to the tank in order to remove the air bubbles from the float surface before measurements are taken.

### 7.4 Role of Compressibility and Thermal Expansion of the Floats in Resurfacing

The effect of the thermal expansion of the float in ballasting is small, and the effect of the float compressibility was contained in the ballasting curve, so it was not explicitly revealed. However, both significantly affect resurfacing in the actual sea. From the vertical profile of water temperature and salinity actually obtained by a float (Fig. 8; on the left-hand side), the effects of compressibility and thermal expansion on float volume during ascent were individually determined, and their contributions to buoyancy are shown in Fig. 8 (on the right-hand side). Here, their contributions at the parking depth were assumed to be zero. According to these results showing the contribution to buoyancy by thermal expansion of the float volume during ascent, although the pressure effect is greater, the change in float volume could not be ignored in warm water shallower than the thermocline.

The compressibility of the float is approximately 50% of that of water. This implies that, during resurfacing from the parking depth, the float itself expands, and its buoyancy is therefore increased by the amount of expansion compared to a float with no compressibility. For instance, if the compressibility of a float is assumed to be the same as that of water, the float will be able to maintain the same density as the surrounding water at any depth, if only the pressure effect is taken into consideration. Furthermore, as the

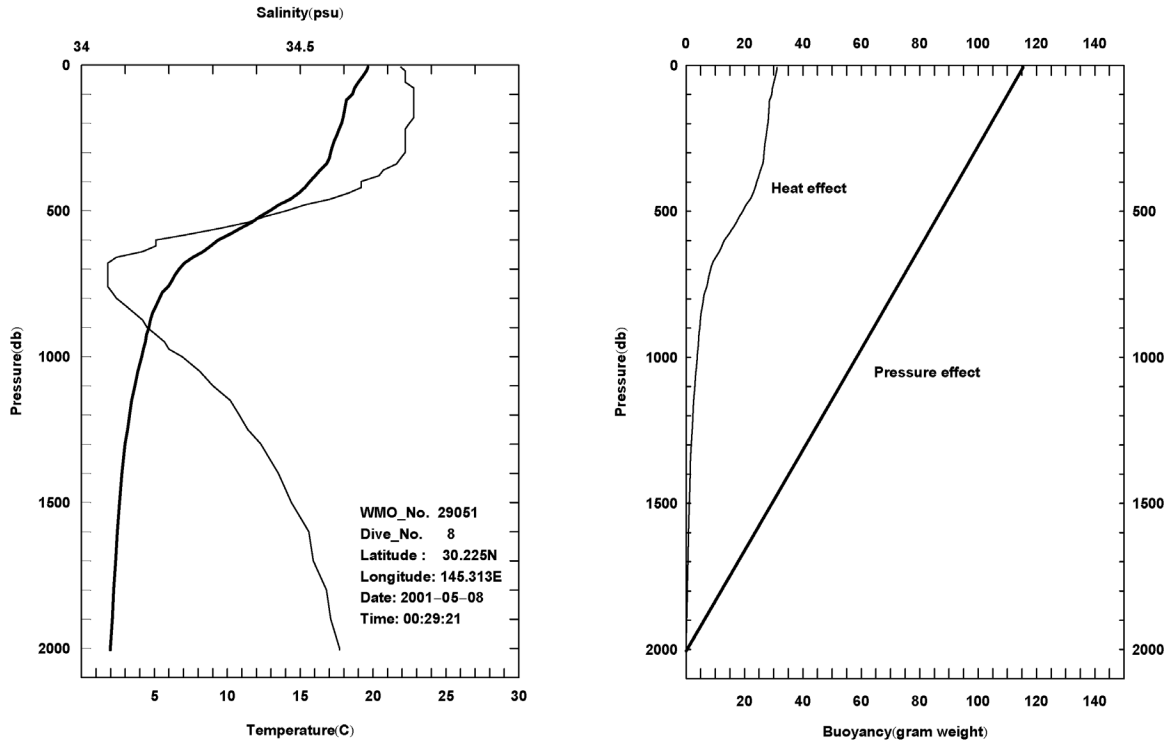


Figure 8. Left panel: An example of vertical temperature/salinity profile observed by a profiling float. Right panel: Contribution to buoyancy of float by heat expansion effect (thin line) and decompression effect (thick line) at the observing (rising) phase shown in the left panel.

temperature is normally higher in the upper layers, the effect of thermal expansion is expected to be greater, so even a small increase in the bladder volume would enable the float to resurface.

The slope of the ballasting curve of the float is proportional to the difference in compressibility between the water and the float ( $\kappa(p) - \gamma$ ), as can be seen from approximation (5). Therefore, when the float has compressibility similar to that of water, the slope will have a value near zero, and the ballasting curve will be a horizontal line parallel to the x-axis, which means that a float will be able to achieve neutral buoyancy at any pressure with the same ballast weight. This also means that a float will not be able to maintain a stable depth. However, it is possible to appropriately increase the compressibility of the float and decrease the slope of the ballasting curve so that smaller ballast will be sufficient. Increasing the float compressibility to a certain extent will have the advantage of reducing the bladder volume necessary for resurfacing.

As previously mentioned, when the parking depth is set at 2,000 m, existing floats will not have adequate buoyancy for resurfacing in the tropical Pacific or the eastern Indian Ocean. For the worldwide deployment of the floats, larger bladder oil volumes are required. The bladder oil volume of Webb APEX-type floats that use a motor-driven piston can be increased, in principle, by changing the length or radius of the piston. However, increasing the design size of the float will result in increased power consumption and changes in the design of the float interior; therefore, in practice, increasing the bladder oil volume is not as simple as it may seem. As discussed above, increas-

ing the compressibility of the float will significantly increase its buoyancy, so it is concluded that consideration should be given to this method and other methods of increasing float buoyancy.

## 8. Conclusions

In this paper, the actual state of oceans in different regions were examined to determine the conditions necessary for a float to achieve neutral buoyancy at a depth of 2,000 m. In addition, the resurfacing capabilities of the float were analyzed. The importance of ballasting experiments for neutrally buoyancy at a depth of 2,000 m was discussed, and the method of ballasting using pressure tanks at JAMSTEC was described in detail. The required precision and points to note in the ballasting experiments were also discussed. The following are the main conclusions:

- (1) Based on the in situ seawater density distribution at a depth of 2,000 m in the tropical and subtropical Pacific, a 1-g change in the weight of existing floats will result in a difference of 10 m in parking depth. However, if the temperature and in situ density of seawater at that depth is spatially uniform and stable, a float that has reached a state of neutral buoyancy and stopped will remain at that depth.
- (2) With the present bladder volume, a float does not have adequate buoyancy to resurface with certainty in the western tropical Pacific or the eastern Indian Ocean. Therefore, the resurfacing capability of the float must be maximized in a wide region, so precision ballasting is required.
- (3) In order for the float to achieve a state of neutral buoyancy, the densities of the seawater and the float must coincide. The temperature and density of seawater at the park-

ing depth can be estimated with a high degree of precision. The float weight must be adjusted to these values in accordance with the change in float volume caused by pressure and temperature changes, which can be determined from experiments using pressure tanks.

(4) The weight to be added to the float can be determined from the ballasting curve, which is the linear regression equation for the relationship between the pressure inside the tank and the weight of the chain lifted by the float in the pressure tank experiment.

(5) To perform precise ballasting, a high degree of precision is required of the ballasting curve. It is also important to make precise measurements of the weights of the chain, ring weights, and attachment, and to control precisely the temperature of the water inside the tank.

(6) The change in float volume during ascent caused by the change in temperature and pressure is extremely effective in increasing the buoyancy of the float, and a float with high compressibility will have the advantage of requiring a smaller bladder volume.

Equipping the float with a larger bladder can solve the problem of the lack of buoyancy of the float in specific regions. However, floats with smaller bladders and hence lower power consumption are more suited to long-term operations. A model of a float with a high degree of buoyancy exists (the Provor), but it has a shorter operational life, requires more battery power, and is larger. In the future, deployment from volunteer vessels will become necessary for large-scale deployment of the floats, so more compact float designs will be required. For this purpose, smaller bladders will become necessary to reduce the number of onboard batteries and the float size. Ballasting will be a necessary procedure in the future to handle floats with smaller bladder volumes.

## 9. Acknowledgements

Prior to our experiments, we were given the opportunity by the University of Washington and the Scripps Institution of Oceanography to visit their facilities and examine their pressure tanks, ballasting instruments, and experiments. Prof. Riser and Mr. Swift offered a great deal of helpful advice on experimental procedures. Prof. Dufour of the Scripps Institution of Oceanography provided valuable insight into the methods of buoyancy calculation and experimental methods. We would like to express our sincere gratitude to them. Mr. Kuboshita of the Facility and Equipment Division of JAMSTEC and Mr. Kikuma of Marine Works Japan, Ltd. assisted us in the operation of the pressure tanks in the present experiment. This study was conducted as part of the "Construction of the Advanced Ocean Monitoring System (Argo Project)," which in turn is part of the millennium project launched in FY 2000 by the Cabinet Office of Japan.

## Appendix A. Examination of the Linearity of the Ballasting Curve

Generally, the change in seawater density  $\rho$  in conjunction with changes in pressure can be expressed using the

following equation when  $s$ ,  $t$ , and  $p$  are water temperature, salinity, and pressure, respectively (UNESCO, 1981):

$$\rho(s,t,p) = \rho(s,t,0)/(1 - p/K(s,t,p)) \dots (A1)$$

where

$$K(s,t,p) = K(s,t,0) + Ap + Bp^2.$$

Here,  $K$  is the bulk modulus, and  $A$  and  $B$  are both functions of  $t$  and  $s$ . This gives the average pressure necessary to compress a unit volume of seawater based on the ratio of compression of seawater from 1 atm ( $p = 0$ ) to pressure  $p$ . It is the inverse of the compressibility (the ratio of compression when pressure  $p$  is applied).

As specified in the main text, in the pressure tank experiments,  $s = 0$ , and  $t$  can basically be considered a constant, so  $t = t_0$ . Therefore, both  $A$  and  $B$  are constants, and  $K$  becomes a quadratic function of only  $p$ . Equation (A1) can be rewritten using compressibility  $\kappa$ ; ( $\kappa(p) = 1/K(p)$ ).

$$\rho(p) = \rho(0)/(1 - p\kappa(p)) \dots (A2)$$

When this equation is substituted into equation (4) in the main text, we obtain

$$M(p) = \rho(0)V_0(1 - \gamma p)/(1 - p\kappa(p)) - M_f \dots (A3)$$

In the variable term in this equation,  $(1 - \gamma p)/(1 - p\kappa(p))$ , the numerator represents the effect of compression of the float due to pressure, and the denominator represents the effect of the compression of water. Since the compression ratio of water is higher than that of the float,  $M(p)$  increases along with  $p$ . When the ratios of compressed water volume  $p\kappa(p)$  are calculated for various cases (Table A1), they are all found to have small values of less than 1%, and  $\gamma p$  is normally approximately half of that value. Therefore, the term containing the variable  $p$  on the right-hand side of equation (A3) can be approximated fairly well using the following equation (error of less than 0.005%):

$$(1 - \gamma p)/(1 - p\kappa(p)) \approx 1 + (\kappa(p) - \gamma p) \dots (A4)$$

When this equation is substituted in equation (A3), we obtain

$$M(p) \approx \rho(0)V_0(\kappa(p) - \gamma p) + (\rho(0)V_0 - M_f) \dots (A5)$$

Since  $\kappa(p)$  on the right-hand side of the equation is almost constant for  $p$  (a change of 3% for a pressure change of 0 to 2,000 db), the graph for equation (A5) is expected to display a nearly linear relationship.

To be precise,  $M(p)$  is a complex fractional function of  $p$ . However, the graph for this fractional function displays a nearly linear relationship (Fig. A1) (when  $t = 9.2^\circ\text{C}$ ,  $\gamma = 2.23 \times 10^{-5}/\text{db}$ ,  $V_0 = 24975.5 \text{ cm}^3$ , and for  $p = 0$  and  $M(p) = 0$ ). When a linear function is approximated for this function, the regression line  $(1.221 + 0.06112 \times 10^{-5}p)$  in Fig. A1 (dashed line) is obtained. The fitness of the linear regression line had a standard deviation of 0.455 g, and did not

change when calculations were made at different temperatures (Table A2). This error corresponds to a difference of 4-5 m in parking depth in the actual sea but, as it is within the allowable range, a straight-line approximation is believed to be sufficient in this case.

Table A1. Ratio of compressed volume

	0db	500db	1000db	1500db	2000db
0°C	0	0.00252342	0.00500574	0.00744782	0.00885047
10°C	0	0.00237190	0.00470730	0.00700887	0.00827170
20°C	0	0.00227730	0.00452054	0.00673051	0.0080797
30°C	0	0.00222178	0.00441058	0.00656724	0.0088250

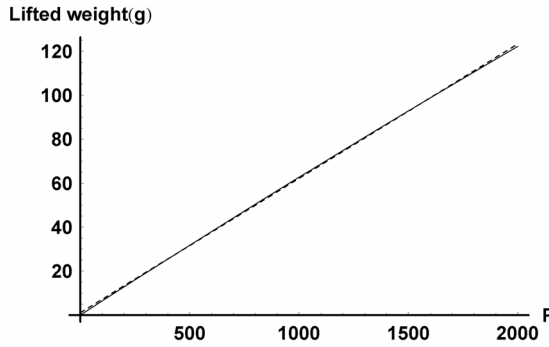


Figure A1. Theoretical ballasting curve (solid line) and fitted linear curve by least square method (dashed line).

Table A2. Fitness of linear fitting curve in terms of tank water temperature.

Temperature(°C)	Error (RMS)
0	0.50
10	0.45
20	0.42
30	0.41

## Appendix B. Points to Note Concerning the Weight in Air and Water of Floats and Weights

Since the weights of the float and ring weights are measured in air, a precise correction must be made for buoyancy due to air. Here, the effect of the buoyancy due to air is evaluated for the float, ring weights, chain, and attachment. In the main text, the weights in water of equipment other than the float were treated as constants regardless of the water pressure, and the validity of this assumption is also evaluated.

### B.1. Effect of Buoyancy Due to Air on the Weights of the Float, etc.

The density of air at 1 atm is a function of the temperature and humidity. According to the Chronological Scientific Tables (National Astronomical Observatory 1990), the density of air in the temperature range of 0-30°C and hu-

midity of 0-100% ranges from 1.146-1.293 g/l. If the density of air is assumed to be 1.2 g/l, since the float volume is approximately 25 liters, the buoyancy due to air is approximately 30 g, which is not negligible.

As specified in the main text, the float volume at 1 atm ( $V_0$ ) can be determined precisely from the ballasting curve, but the approximate volume can be estimated from the rough ballasting. In the rough ballasting, the float is placed in the water with its top slightly above the surface, and ring weights are added gradually to increase the float weight. The ring weights are 25 g or 50 g each. When the addition of a ring weight sinks the float, the weight of the added ring ( $m_w'$ ) exceeds the weight to be added to the float to achieve neutral buoyancy, but the error is less than 25 g. Air bubbles that form on the float surface also cause errors (empirically approximately 10 g under normal conditions) but, even when this effect is taken into consideration, a conservative estimate can be made of the weight with a precision of better than 50 g. In this case, when the float is assumed to be in a state of neutral buoyancy, the following approximation can be made:

$$V_0\rho = M_f' + V_0\rho_a + m_w' \dots (B1)$$

Here,  $M_f'$  is the float weight measured in air, and  $\rho_a$  is the density of air. The weight of the rings  $m_w'$  is also a value measured in air, so it is affected by the buoyancy due to air. As specified in the main text, the maximum total weight of the ring weights, attachment, and chain was set at 200 g, so  $m_w'$  is less than 200 g. The density of the 18-8 stainless steel (SUS304), which is the material used for the rings, is 7.9 g/cm<sup>3</sup> (The Japan Society of Mechanical Engineers, 1993), so the ring volume does not exceed 25 cm<sup>3</sup>. Therefore, the buoyancy due to air acting on the rings is 0.03 g at most, and can be ignored.

The approximate value of the float volume  $V_0$  can be expressed as follows based on equation (B1):

$$V_0 = (M_f' + m_w') / (\rho - \rho_a) \dots (B2)$$

The right-hand side of the above equation is the approximate float volume, and since the error due to  $m_w'$  is less than 50 g and the denominator is approximately 1 (g/cm<sup>3</sup>), the error of the approximation is less than 50 cm<sup>3</sup>.

Since the buoyancy due to air acting on the float is  $V_0\rho_a$ , the error in the estimation of buoyancy when the estimated value above is used is no more than 0.06 g, and is more precise than the measurement of  $M_f'$ , which is 0.5 g, so this can be considered a sufficient approximation. Therefore, the buoyancy due to air can be estimated using the approximate float volume obtained from the rough ballasting, and the real weight of the float  $M_f$  can be obtained by adding the air buoyancy to  $M_f'$ .

Actually, the working accuracy of the float volume for floats in the same lot is expected to be far better than 50 cm<sup>3</sup>, so the value of the air-buoyancy correction need not be determined for each float; adding a constant value for the correction is considered sufficient.

In addition, as previously mentioned, the ring volume is sufficiently small that there is no need for air-buoyancy correction. The attachment and chain are made of the same material as the rings, so their volumes are also sufficiently small to require no correction for air buoyancy.

## B.2. Compression of the Chain, etc. in Water and Change in Buoyancy

The chain, attachment, and ring weights are all made of 18-8 stainless steel (SUS304), the bulk modulus ( $K$ ) of which is given by the following equation:

$$K = E/[3(1 - 2\nu)]$$

Here,  $E$  is the longitudinal modulus and  $\nu$  is Poisson's ratio. Their values are 189 [Gpa] and 0.2, respectively (Japan Society of Mechanical Engineers 1993). Therefore, the bulk modulus  $K$  is 105 [Gpa]. When  $V$  is the volume of the chain, attachment, and ring weights at 1 atm,  $p$  is the tank water pressure, and the compression at this pressure is  $\Delta V$ , then

$$p = K\Delta V/V.$$

At 2,000 db (20 MPa), the compression ratio  $\Delta V/V$  is approximately 0.0002. Since the total weight of the ring weight, chain, and attachment is less than 200 [g],  $V$  does not exceed 25 cm<sup>3</sup>, so  $\Delta V$  is no more than 0.005 [cm<sup>3</sup>]. Therefore, the volume can be considered constant.

On the other hand, the buoyancy acting on the ring, chain, and attachment is also dependent on changes in water density with changes in the water pressure. The density of water at 2,000 db is approximately 1% higher than that at 1 atm (see Table A1). As buoyancy is the product of volume and density, the increase in buoyancy is no more than 0.25 g. The weight in water decreases due to this buoyancy, but the change in weight can be ignored due to the required ballasting precision.

## Appendix C. Data-Processing Method for the Ballasting Experiment

Software for Windows was developed to process the data obtained in the ballasting experiment. The program was written in Visual Basic, but here the program is presented in N<sub>88</sub>-Japanese BASIC (86) for greater versatility.

In this program, the set of measurement data for the pressure and the length of chain lifted by the float in the pressure tank experiment are given as input to calculate the ballasting curve. Based on this calculated ballasting curve, the weight of the ballast to be added to the float in order to achieve neutral buoyancy at a specified depth is obtained.

For detailed instructions on the program, the user is referred the comment lines at the head of the program list.

In the program list, the DATA statements from lines 1540 to 1740 are actual experimental results. The DATA statements contain the sampling number, the length of chain lifted at each pressure, the weight of the chain per unit length, the weight of the ring weights, and the initial weight of the float. As the in situ water temperature, salin-

ity, and pressure at the parking depth are normally constant, they are defined separately from the DATA statements. In the Windows version, a graphical user interface (Fig. C1) is provided as a user-friendly method for entering data, but the essential data processing is the same as that presented here.

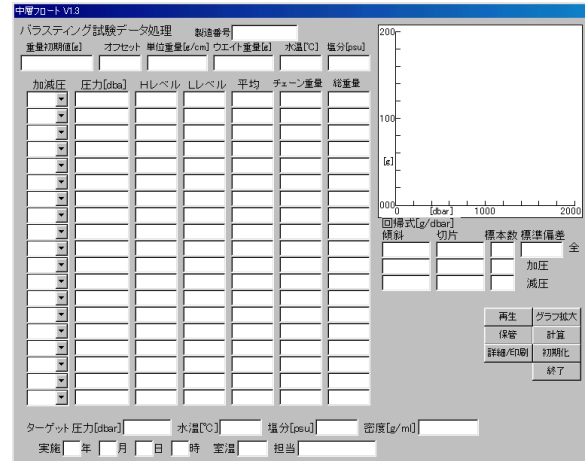


Figure C1. Graphical user interface of a program for ballasting experiments using pressure tank.

This program is available at <http://www.jamstec.go.jp/J-ARGO/> for user reference.

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## Program List

```
1000 ' SAVE "BALLAST.BAS"
1010 '
1020 '1) Summary
1030 ' This software is used in ballasting of the profiling
floats.
1040 '
1050 '
1060 ' The ballasting curve is determined from the pressure
and the length of chain lifted by the float measured in
the pressure tank, to determine the weight of the
ballast required to keep the float at the parking depth
(provide the float with density equal to that of the
seawater).
1070 '
1080 '
1090 '
1100 '2) Necessary Data and How to Input It
1110 ' @ Input data from the pressure experiment
1120 ' by editing the DATA statement.
1130 ' The DATA statement is in the following order.
1140 ' (H) and (L) are for cases involving oscillation.
1150 '
1160 ' Sampling Number N
1170 ' Pressure 1, Lifted Length (H) 1, Lifted Length (L) 1
1180 ' Pressure 2, Lifted Length (H) 2, Lifted Length (L) 2
1190 ' @
1200 ' @
1210 ' @
1220 ' @
1230 ' Pressure N, Lifted Length (H) N, Lifted Length (L)
N
1240 ' Weight of chain per unit length
1250 ' Weight of chain
1260 ' Initial weight of float
1270 ' Tank water temperature
1280 '
1290 ' @ Conditions at Parking Depth
1300 ' Edit the following variables under the DATA state-
ment.
1310 '
1320 ' O.TEMP# = 5.13# ' In situ temperature at parking
depth
1330 ' O.SALT# = 34.325# ' In situ salinity at parking
depth
1340 ' TP# = 2000# ' Pressure at parking depth
1350 '
1360 ' @ Tank water salinity
1370 '
1380 ' T.SALT# = 0# ' Tank water salinity (normally 0)
1390 '
1400 '3) Units
1410 ' The following units are used in this software.
1420 ' Salinity [psu]
1430 ' Water temperature [°C]
1440 ' Pressure [db]
1450 ' Weight [g]
1460 ' Density [g/cm^3]
1470 '
1480 '
1490 '4) Other
1500 ' Double-precision floating-point numbers are used
for calculations.
1510 '
1520 '
1530 '
1540 ' ***** Experimental Data
*****
1550 '
1560 ' APEX-SBE SN.225 Ballasting Data
1570 ' Date of Experiment: February 1, 2001
1580 '
1590 DATA 11 ' Sampling Number
1600 DATA 1920.1, 38.8, 38.8
1610 DATA 1818.4, 31.2, 31.2
1620 DATA 1727.7, 24.2, 24.2
1630 DATA 1623.4, 16.2, 16.2
1640 DATA 1526.6, 9.4, 9.4
1650 DATA 1427.5, 1.4, 1.4
1660 DATA 1477.2, 4.8, 4.8
1670 DATA 1578.5, 12.6, 12.6
1680 DATA 1675.8, 19.8, 19.8
1690 DATA 1773.4, 27.4, 27.4
1700 DATA 1871.8, 34.6, 34.6
1710 DATA 0.808 ' Weight of chain per unit length
1720 DATA 4.34 ' Weight of chain
1730 DATA 25050.5 ' Initial weight of float
1740 DATA 9.2 ' Tank water temperature
1750 '
1760 *****
1770 '
1780 O.TEMP# = 2# ' In situ temperature at parking depth
1790 O.SALT# = 34.6# ' In situ salinity at parking depth
1800 TP# = 2000# ' Pressure at parking depth
1810 '
1820 T.SALT# = 0# ' Tank water salinity
1830 '
1840 AL.TXP# = .000069# ' Coefficient of thermal expan-
sion of aluminum body
1850 '
1860 '
1870 ' ***** Coefficients for Density Calculation *****
1880 '
1890 ZB0# = .824493#
1900 ZB1# = -.0040899#
1910 ZB2# = .000076438#
1920 ZB3# = -.00000082467#
1930 ZB4# = .0000000053875#
1940 '
1950 ZC0# = -.00572466#
1960 ZC1# = .00010227#
1970 ZC2# = -.0000016546#
1980 '
1990 ZD0# = .00048314#
2000 '

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2010 ZA0# = 999.842594#
2020 ZA1# = .06793952#
2030 ZA2# = -.00909529#
2040 ZA3# = .0001001685#
2050 ZA4# = -.000001120083#
2060 ZA5# = .000000006536332#
2070 '
2080 ZF0# = 54.6746#
2090 ZF1# = -.603459#
2100 ZF2# = .0109987#
2110 ZF3# = -.00006167#
2120 '
2130 ZG0# = .07944#
2140 ZG1# = .016483#
2150 ZG2# = -.00053009#
2160 '
2170 ZI0# = .0022838#
2180 ZI1# = -.000010981#
2190 ZI2# = -.0000016078#
2200 '
2210 ZJ0# = .000191075#
2220 '
2230 ZM0# = -.00000099348#
2240 ZM1# = .000000020816#
2250 ZM2# = .00000000091697#
2260 '
2270 ZE0# = 19652.21#
2280 ZE1# = 148.4206#
2290 ZE2# = -2.327105#
2300 ZE3# = .01360477#
2310 ZE4# = -.00005155288#
2320 '
2330 ZH0# = 3.239908#
2340 ZH1# = .00143713#
2350 ZH2# = .000116092#
2360 ZH3# = -.000000577905#
2370 '
2380 ZK0# = .0000850935#
2390 ZK1# = -.00000612293#
2400 ZK2# = .000000052787#
2410 '
2420 '
2430 ' ***** Main Routine *****
2440 '
2450 *MAIN
2460 '
2470 ' --- Read Data---
2480 '
2490 READ N
2500 DIM PRESS#(N), HLEVEL#(N), LLEVEL#(N),
      M.CHAIN#(N), V.CHAIN#(N)
2510 DIM DX(N), DY(N), CAL#(N), MASS#(N),
      DEN#(N), VOL#(N)
2520 '
2530 FOR J = 1 TO N
2540 READ PRESS#(J)
2550 READ HLEVEL#(J)
2560 READ LLEVEL#(J)
2570 NEXT J
2580 '
2590 READ W.CHAIN# ' Weight of chain per unit length
2600 READ M.REMOVE# ' Weight of ring weight
2610 READ INIT.MASS# ' Initial weight of float
2620 READ T.TEMP# ' Tank water temperature
2630 '
2640 ' --- Calculation of Weight of Chain and Ring Weights
      ---
2650 '
2660 FOR J = 1 TO N
2670 M.CHAIN#(J) =
      (HLEVEL#(J)+LLEVEL#(J))/2*W.CHAIN#+M.RE
      MOVE#
2680 NEXT J
2690 '
2700 '
2710 ' --- Calculation of the Ballasting Curve by the
      Least-Squares Method ---
2720 '
2730 FOR J = 1 TO N
2740 DX(J) = PRESS#(J)
2750 DY(J) = M.CHAIN#(J)
2760 NEXT J
2770 GOSUB *KAIKI
2780 AA = A ' Intercept of ballasting curve
2790 BB = B ' Slope
2800 STD.DEV = DEV ' Standard deviation
2810 '
2820 ' --- Calculation of Tank Water Density ---
2830 '
2840 T# = T.TEMP#
2850 S# = T.SALT#
2860 P# = TP# / 10#
2870 GOSUB *DENSITY
2880 T.DENS# = ZRSTP# / 1000#
2890 '
2900 ' --- Calculation of Seawater Density at Parking Depth
      ---
2910 '
2920 T# = O.TEMP#
2930 S# = O.SALT#
2940 P# = TP# / 10#
2950 GOSUB *DENSITY
2960 O.DENS# = ZRSTP# / 1000#
2970 '
2980 ' --- of Float Volume at 1 Atm Calculation (at Tem-
      perature t0) ---
2990 '
3000 T# = T.TEMP#
3010 S# = 0
3020 P# = 0
3030 GOSUB *DENSITY
3040 INIT.DENS# = ZRSTP# / 1000
3050 INIT.VOL# = (INIT.MASS# + AA) / INIT.DENS#
3060 '
3070 ' --- Various Calculations ---
3080 '

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3090 T.MASS# = INIT.MASS# + BB*TP# + AA
3100 T.BALLAST# = BB*TP# + AA
3110 T.VOL# = T.MASS# / T.DENS#
3120   D.VOL#   =   T.VOL#*(O.TEMP#   -
      T.TEMP#)*AL.TXP#
3130 O.VOL# = T.VOL# + D.VOL#
3140 O.MASS# = O.VOL# * O.DENS#
3150 C.MASS# = O.MASS# - T.MASS#
3160 O.BALLAST# = T.BALLAST# + C.MASS#
3170 '
3180 *DISP
3190 PRINT USING "Ballasting Curve M(P)[g]
      =##.#####*P[db] +###.##"; BB,AA
3200 '
3210 PRINT USING "Standard Deviation   ##.## [g]";
STD.DEV
3220 PRINT
3230 '
3240 PRINT "Pressure at Parking Depth";
3250 PRINT USING "##### [db]"; TP#
3260 '
3270 PRINT "In Situ Temperature at Parking Depth";
3280 PRINT USING "###.## "; O.TEMP#;
3290 PRINT "[°C]"
3300 '
3310 PRINT "In Situ Salinity at Parking Depth";
3320 PRINT USING "###.### [psu]"; O.SALT#
3330 '
3340 PRINT "In Situ Density at Parking Depth";
3350 PRINT USING "#.##### [g/cm^3]"; O.DENS#
3360 '
3370 PRINT "Initial Weight of Float";
3380 PRINT USING "#####.## [g]"; INIT.MASS#
3390 '
3400 PRINT "Weight of Chain Per Unit Length in Water";
3410 PRINT USING "###.### [g]"; W.CHAIN#
3420 '
3430 PRINT "Weight of Ring Weight in Water (Including
      Attachment)";
3440 PRINT USING "###.## [g]"; M.REMOVE#
3450 '
3460 PRINT "Coefficient of Thermal Expansion of Float";
3470 PRINT USING "#.#E-05"; AL.TXP# * 100000#;
3480 PRINT "[/°C]"
3490 '
3500 PRINT "Tank Water Pressure";
3510 PRINT USING "##### [db]"; TP#
3520 '
3530 PRINT "Tank Water Temperature";
3540 PRINT USING "###.###"; T.TEMP#;
3550 PRINT "[°C]"
3560 '
3570 PRINT "Tank Water Density";
3580 PRINT USING "#.##### [g/cm^3]"; T.DENS#
3590 '
3600 PRINT "Added Weight to the Float in the Tank";
3610 PRINT USING "###.## [g]"; T.BALLAST#
3620 '
3630 PRINT "Total Weight of the Float in the Tank";
3640 PRINT USING "#####.## [g]"; T.BALLAST# +
      INIT.MASS#
3650 '
3660 PRINT "Float Volume in the Tank";
3670 PRINT USING "#####.## [cm^3]"; T.VOL#
3680 '
3690 PRINT "Float Volume at 1 Atm (at Temperature t0)";
3700 PRINT USING "#####.## [cm^3] "; INIT.VOL#
3710 '
3720 PRINT "Float Volume at Parking Depth ";
3730 PRINT USING "#####.## [cm^3]"; O.VOL#
3740 '
3750 PRINT "Float Weight at Parking Depth";
3760 PRINT USING "#####.## [g]"; O.MASS#
3770 '
3780 PRINT "Ballast Weight";
3790 PRINT USING "###.## [g]"; O.BALLAST#
3800 '
3810 END
3820 '
3830 ***** Regression Calculation by the Least-Squares
      Method *****
3840 '
3850 *KAIKI
3860 ZX = 0
3870 FOR J = 1 TO N
3880 ZX = ZX + DX(J)
3890 NEXT J
3900 '
3910 ZY = 0
3920 FOR J = 1 TO N
3930 ZY = ZY + DY(J)
3940 NEXT J
3950 '
3960 ZXY = 0
3970 FOR J = 1 TO N
3980 ZXY = ZXY + DX(J)*DY(J)
3990 NEXT J
4000 '
4010 ZXZY = ZX*ZY
4020 '
4030 ZXX = 0
4040 FOR J = 1 TO N
4050 ZXX = ZXX + DX(J)*DX(J)
4060 NEXT J
4070 '
4080 IF (N*ZXX - ZX*ZX)= 0 THEN B = 1 : A = 0 :
      GOTO *KAIKI2
4090 '
4100 B = (N *ZXY - ZX*ZY)/(N *ZXX - ZX*ZX) ' Slope
4110 A = ZY/N - B *ZX/N ' Intercept
4120 '
4130 '
4140 ***** Calculation of Standard Deviation *****
4150 *KAIKI2
4160 DEV1= 0
4170 DEV2= 0

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4180 '
4190 FOR J = 1 TO N
4200 CAL#(J) = B *DX(J) + A
4210 CE = CAL#(J) - DY(J)
4220 DEV1 = DEV1 + CE * CE
4230 DEV2 = DEV2 + CE
4240 NEXT J
4250 DEV = SQR((N * DEV1 -DEV2*DEV2)/N/(N-2))
4260 RETURN
4270 '
4280 '
4290 '
4300 ' ***** Calculation of Seawater Density *****
4310 '
4320 ' Seawater density is calculated from salinity S#,
      temperature T#, and pressure P#.
4330 '
4340 *DENSITY
4350 T2# = T#*T#
4360 T3# = T2#*T#
4370 T4# = T3#*T#
4380 T5# = T4#*T#
4390 '
4400 ZRW# = ZA0# + ZA1#*T# + ZA2#*T2# +
      ZA3#*T3# + ZA4#*T4# + ZA5#*T5#

4410 ZRST0# = ZRW# +(ZB0# + ZB1#*T# + ZB2#*T2#
      + ZB3#*T3# + ZB4#*T4#) *S#
4420 ZRST0# = ZRST0# + (ZC0# + ZC1#*T# +
      ZC2#*T2#) *S#^(3/2) + ZD0#*S#*S#
4430 '
4440 ZKW# = ZE0# + ZE1#*T# + ZE2#*T2# + ZE3#*T3#
      + ZE4#*T4#
4450 ZAW# = ZH0# + ZH1#*T# + ZH2#*T2# +
      ZH3#*T3#
4460 ZBW# = ZK0# + ZK1#*T# + ZK2#*T2#
4470 '
4480 ZA# = ZAW# + (ZI0# + ZI1#*T# + ZI2#*T2#)*S# +
      ZJ0#*S#^(3/2)
4490 ZB# = ZBW# + (ZM0# + ZM1#*T# +
      ZM2#*T2#)*S#
4500 '
4510 ZKST0# = ZKW# + (ZF0# + ZF1#*T# + ZF2#*T2#
      + ZF3#*T3#)*S# + (ZG0# + ZG1#*T# +
      ZG2#*T2#)*S#^(3/2)
4520 '
4530 ZKSTP# = ZKST0# + ZA#*P# + ZB#*P#*P#
4540 '
4550 ZRSTP# = ZRST0#/(1# - P#/ZKSTP#)

```