capsized. It is also possible that equilibrium would not be reached until the angle of heel became so large that water would be shipped through topside openings, and that the weight of this water, running to the low side of the ship, would contribute to capsizing which otherwise would not have occurred.

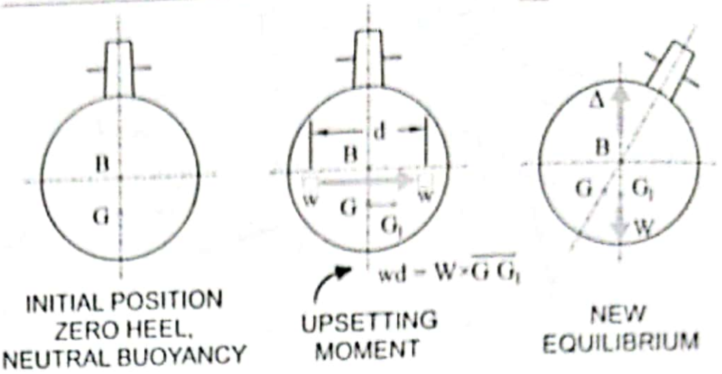
Upsetting forces act to incline a ship in the longitudinal as well as the transverse direction. Since a surface ship is much stiffer, however, in the longitudinal direction, many forces, such as wind pressure or towline strain, would not have any significant effect in inclining the ship longitudinally. Shifting of weights aboard in a longitudinal direction can cause large changes in the attitude of the ship because the weights can be moved much farther than in the transverse direction. When very heavy lifts are to be attempted, as in salvage work, they are usually made over the bow or stern rather than over the side, and large longitudinal inclinations may be involved in these operations. Stranding at the bow or stern can produce substantial changes in trim. In each case, the principles are the same as previously discussed for transverse inclinations. When a weight is shifted longitudinally or lifted over the bow or stern, the CG of the ship will move, and the ship will trim until the center of buoyancy is directly below the new position of the CG. If a ship is grounded at the bow or stern, it will assume an attitude such that the moments of weight and buoyancy about the point of contact are equal.

In the case of a submerged submarine, the center of buoyancy is fixed, and a given upsetting moment produces very nearly the same inclination in the longitudinal direction as it does in the transverse direction (Fig. 12). The only difference, which is trivial, is because of the effect of liquids aboard which may move to a different extent in the two directions. A submerged submarine, however, is comparatively free from large upsetting forces. Shifting of the CG as the result of weight changes is carefully avoided. For example, when a torpedo is fired, its weight is immediately replaced by an equal weight of water at the same location.

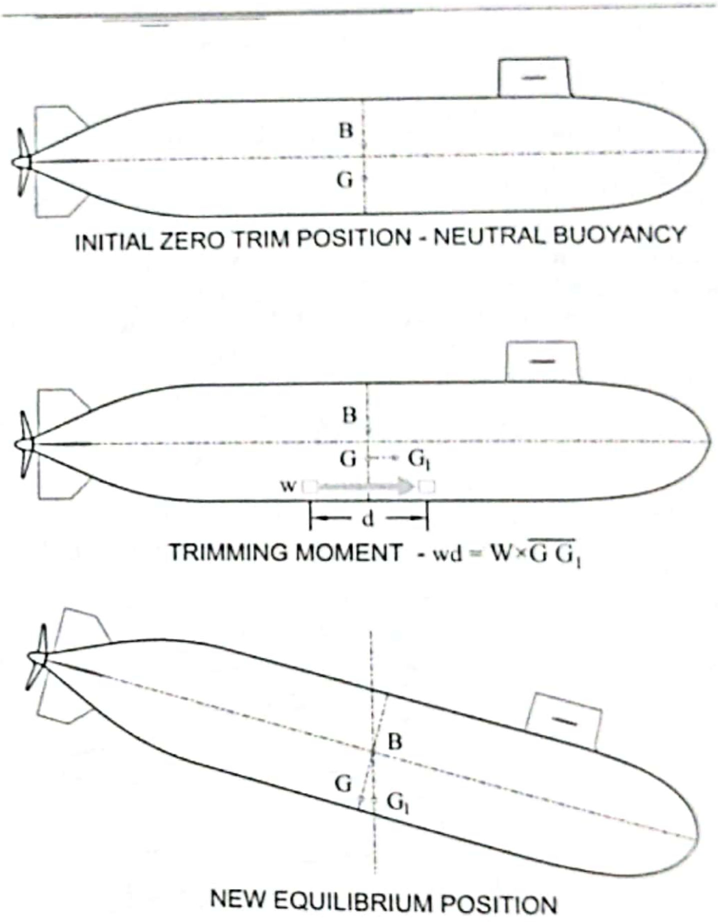
1.7 Submerged Equilibrium. Before a submarine is submerged, considerable effort has been expended, both in design and operation, to ensure that:

- The weight of the submarine, with its loads and ballast, will be very nearly equal to the weight of the water it will displace when submerged.
- The CG of these weights will be very nearly in the same longitudinal position as the center of buoyancy of the submerged submarine.
- The CG of these weights will be lower than the center of buoyancy of the submerged submarine.

These precautions produce favorable conditions that are described, respectively, as neutral buoyancy, zero trim, and positive stability. A submarine on the surface, with weights adjusted so that the first two conditions will be satisfied upon filling the main ballast tanks, is said to be in diving trim.



a) TRANSVERSE STABILITY



b) LONGITUDINAL STABILITY

Fig. 12 Effect of weight shift on the transverse and longitudinal stability of a submerged submarine.

The effect of this situation is that the submarine, insofar as transverse and longitudinal stability are concerned, acts in the same manner as a pendulum. This imaginary pendulum is supported at the center of buoyancy, has a length equal to the separation of the centers of buoyancy and gravity, and a weight equal to the weight of the submarine.

It is not practical to achieve an exact balance of weight and buoyancy or to bring the CG precisely to the same longitudinal position as the center of buoyancy. It is also not necessary, since minor deviations can be counteracted by the effect of the bow and stern planes when underway submerged.

fleet of small commercial fishing vessels in a very complex dynamic environment. For example, the smaller the boat, the more significant the sea conditions are. This is shown by contemplating the effect of 6 m seas on a 300 m tanker, a 45 m trawler, or a 15 m offshore lobster boat. The 6 m seas are no concern for the tanker, minimal concern for the trawler, and significant concern for the lobster boat. The existing stability criteria do not reflect this conflict due to scalability problems with the Torremolinos area criteria and the lack of true dynamic analysis methods. Womack (2002) goes on to outline the steps required for a satisfactory stability analysis and evaluation and the equally important presentation of the stability guidance and stability concepts to the crews.

7.6.2 Towboats. Towboats may also be prone to sea–motion-related capsizing. In addition, these ship types are characteristically designed with low freeboard, which enhances the danger of taking on sea water through topside openings. Other hazards frequently experienced by tugs are the towline forces generated by the tug's own propeller thrust, called self-tripping, and by the movement of the ship being towed, called tow-tripping. Towboats must meet the general stability criteria, such as the USCG stability criteria (CFR 174.145); however, the heeling arm developed below will usually dominate.

7.6.2.1 HEELING ARM. The formula for calculating the transverse heeling arm curve for tow-line pull, used by the USCG (CFR 173.095), is as follows (metric units):

$$\text{Heeling Arm} = \frac{2N(P \times D)^{2/3} \times s \times h \times \cos\phi}{13.93\Delta} \qquad (29)$$

where:

N = number of propellers

P = shaft horsepower per shaft, kilowatts

D = propeller diameter, m

s = effective fraction of propeller slip stream deflected by the rudder, assumed to be that fraction of the propeller circle cylinder which would be intercepted by the rudder if turned to 45 degrees from the vessel's centerline

h = vertical distance from propeller shaft centerline at rudder to towing bitts, m

Δ = displacement, t

ϕ = angle of inclination

7.6.2.2 CRITERIA FOR ADEQUATE STABILITY. The U.S. Navy criteria for adequate stability are based on the angle of heel and a comparison of the ship's righting arm and the heeling arm curve (see Fig. 58). Stability is considered satisfactory if:

- The angle of heel, as indicated by point *C*, does not exceed the angle at which unrestricted downflooding may occur, or 40 degrees, whichever is less. The limit on range is to provide a margin of safety in the event a watertight door or vent duct is open and could be a pathway for serious downflooding due to wave and heel action.
- The heeling arm at the interception of the righting arm and heeling arm curves (point *C*) is not more than six tenths of the maximum righting arm.
- The reserve of dynamic stability (shaded area) is not less than four tenths of the total area under the righting arm curve. The USCG criterion is similar to the navy criterion except that it requires the reserve of dynamic stability to be 0.61 m-degrees (0.01065 m-radians).

7.6.3 BULK CARRIERS CARRYING GRAIN. Once the grain heeling moment has been computed (see Section 5.14), the IMO (1991) and national regulations require that the angle of heel due to the shift of grain be less than the lesser of 12 degrees or the angle at which the deck edge immerses. The grain heeling moment is then applied as a heeling arm curve for comparison to the righting arm curve. The residual area between the two curves (as limited by 40 degrees, the angle of maximum difference between the righting and heeling righting arms, or angle of flooding) must be not less than 0.075 m-radians. Finally, the $\overline{GM}$ including free-surface effects shall not be less than 0.30 m. Recognizing the importance of angle of repose and trimming the cargo, the vessel is required to be upright before proceeding to sea.

7.7 Evaluation of Mobile Offshore Drilling Units. Criteria for stability evaluation of mobile offshore drilling units (MODUs) are included in the 2008 IS Code (IMO, 2008) and updated in classification society rules for construction (American Bureau of Shipping, 2008). Semisubmersible drilling platforms obtain static stability from surface-piercing columns that connect their submerged flotation bodies to the above-water platform. Analysis of their ability to withstand the upsetting forces of winds and waves (under varying loading conditions) is similar to the type of analysis made for conventional ship forms. However, the wind heeling moments applied include the form drag of the various components of the structure, such as the drilling derrick, and the increased exposure of superstructure deck as the MODU heels. In addition, the overturning moment must be considered for all axes of heel (see Section 4.12).

Stability must be evaluated for all modes of operation of the vessel, including transit, operating, and severe storm conditions. Alternative criteria that take into account the environmental conditions, dynamic response (through wind-tunnel and wave-tank tests or nonlinear simulation, as appropriate), the potential for flooding, the susceptibility for capsizing, and adequate margin for uncertainties may be allowed. The wind speeds associated with the MODU severe storm criteria are 100 knot winds. Hurricanes in the Gulf of Mexico in 2005, where winds far in excess of 100 knots were experienced (NOAA, 2005), led to the loss of several MODUs indicating that sufficient margins may not be included in these criteria.

7.8 Evaluation of Stability of Submarines. The foregoing principles apply to a surfaced submarine as well as to surface ships. There are some peculiarities of submarines, however, which should be mentioned.

The form of the hull of a submarine is such that the righting arms in the surfaced condition are positive at angles well beyond 90 degrees, a condition that is seldom found in surface ships other than sailing yachts and self-righting rescue boats. The only significant heeling moment to which a surfaced submarine is subjected results from wind and wave action. Unlike surface ships, all topside openings can be closed to prevent shipping of water during heavy rolling except for the old diesel-powered submarines that must operate with open diesel engine manifolds. Consequently, capsizing of an intact submarine is extremely unlikely. The major stability problem is rolling to very large angles with adverse effects on personnel and the operation of the ship.

The righting arm curve for a submerged submarine is equal to the metacentric height, $\overline{GB}$, multiplied by the sine of the angle of inclination. Its maximum value, therefore, occurs at 90 degrees. Except for the minor effect of shifting of liquids and loose items in the ship, the range of positive stability would be 180 degrees. A submarine is subjected to only minor heeling moments when submerged. Therefore, there is no danger of capsizing an intact submerged submarine, provided the metacentric height has at least a small positive value.

During the period while a submarine is submerging or surfacing, its transverse stability is less than when either surfaced or submerged because of the free liquid in the main ballast tanks. On the surface, there is only a small free-surface effect in the main ballast tanks, caused by the small quantity of residual water that cannot be blown whose surface remains above the tops of the flood openings. When the submarine is submerged, there is no free surface in the main ballast tanks because they are completely full.

An approximate evaluation of stability during submerging and surfacing can be made by a series of calculations of displacement, height of the CG of the ship, and the free-surface effect, assuming that the main ballast tanks are filled to successively greater depths. The only variables in these calculations are the weight, VCG, and vertical moment of free surface of the water in the main ballast tanks. The effect of the water in the main ballast tanks at each assumed level is added to the weight, vertical moment, and vertical moment of free surface of the ship in the surfaced condition, after the vertical moment of free surface of the residual water has been deducted.

The results of these calculations, consisting of the displacement and height of the CG of the ship, adjusted for free-surface effect, are plotted in Fig. 59, together with the height of the metacenter; the minimum metacentric height is determined as the smallest vertical distance between the two curves. Stability is satisfactory if the metacentric height has a small positive value because the nature of the righting arm curve during submergence is such that positive values will be developed at small angles of heel when the metacentric height is zero.

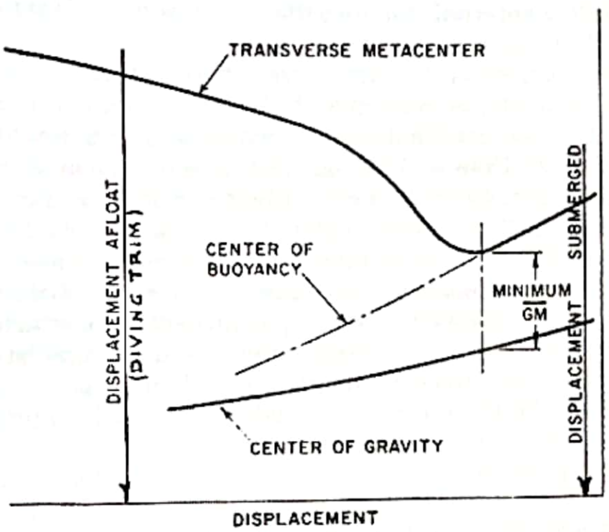


Fig. 59 Submarine stability while submerging.

The height of the metacenter drops as displacement is increasing from its value in the surfaced condition, shown to the left of Fig. 59, until it meets the curve of the height of the center of buoyancy. The vertical separation of these two curves, $\overline{BM}$, is equal to I_T/V, which has been reduced to zero as the ship submerges, owing to the disappearance of the waterplane when the hull is submerged.

The assumption in these calculations that all main ballast tanks are filled to the same waterline is somewhat unrealistic because the actual levels in the various tanks depend on the area of the flood openings, the shape of the individual tanks, and the depths to which the openings are submerged. The flood openings are sized to flood the forward tanks faster than the after tanks to produce a down angle on the submarine and expedite submerging. In addition, any rolling of the submarine will increase the depth to which the tanks on the low side are submerged, causing them to fill faster than those on the high side.

When the main ballast tanks are arranged in pairs, the moment of inertia of the individual port and starboard tanks is used, rather than the moment of inertia of the pair considered as a single tank because there is no flow from one side to the other.

7.9 Review of the International Maritime Organization Intact Stability Code. Several problems have been identified in the existing procedures for stability assessment, especially for vessels that deviate from the ship forms upon which the standards have been based. Operational practice and experience are ways to judge the effectiveness of current stability criteria. Fortunately, accidents that are clearly related to a failure of a ship's intact stability are very rare. The ability to investigate the origin of such accidents is often severely hampered by the depth of water in which the lost ship is located. Those accidents that do avail themselves to full investigation are often associated with several failure events,

(PRINCIP. OF NAVAL ARCH.) SNAME AND 2010 COLIN MOORE

10

Submerged Equilibrium

10.1 Definition. A submerged submarine is in equilibrium when its weight is equal to the buoyancy of the total hull and when its CG is in the same longitudinal position as its center of buoyancy so that it has zero trim. Actually, there may be very small differences between the weight and buoyancy and between the longitudinal positions of the centers of gravity and buoyancy. These differences are overcome by use of submarine's planes when underway in a submerged condition. When a submarine must be dead underwater to maintain silence, it is important that the weight equals the submerged buoyancy exactly.

On the surface, the weight of the submarine is lighter than its submerged displacement, and it is necessary to take on seawater in the ballast tanks to enable the submarine to submerge and be in a condition of equilibrium with zero trim while submerged. There are certain loading conditions on the surface that tend to make the submarine "heavy" or "light." In such cases, ballast water must be carried when on the surface so that upon complete flooding of the main ballast tanks, a submerged condition of equilibrium and zero trim will result. A submarine that is properly designed with respect to weight, buoyancy, and variable ballast tank capacity will always be in diving trim on the surface regardless of the actual load variations and will be able to successfully dive and be in equilibrium with zero trim in a submerged condition with the main ballast tanks full of seawater.

Diving trim, diving ballast, and variable ballast are discussed in Sections 10.2, 10.3, and 10.4.

10.2 Items of Weight. The items of weight that are considered in studies of submerged equilibrium are illustrated in Figs. 63 and 64, and are defined as follows:

10.2.1 Submerged Displacement. The submerged displacement is the displacement of the entire envelope of the ship minus any free flooding spaces. The submerged displacement is fixed by geometry rather than by weight. For a given configuration of the ship, the submerged displacement will vary only with the density of the sea. Weight must be adjusted to conform to the submerged displacement.

10.2.2 Lightship. Lightship is calculated by taking the sum of the weights of the components making up the ship. This weight is fixed unless some alteration to the ship is made.

LEAD SOLID BALLAST

10.2.3 Lead. Solid ballast is the margin in the weight estimate. In submarine design, the volume of the submerged displacement is made larger than the anticipated weight in the submerged condition by a generous margin. Some of this margin is usually needed to compensate for inaccuracies in the weight and displacement calculations or for unexpected installations and future modifications. When the ship is completed, any unexpended margin must be installed as solid ballast to achieve submerged equilibrium. Solid ballast is part of lightship. Lead is most often used as solid ballast material because of its high density and because it causes few corrosion problems.

10.2.4 Load to Submerge. The load to submerge is the weight that must be added to the *lightship—with lead* to bring the ship to a condition of submerged equilibrium. Assuming no changes are made that affect the geometry or weight of the ship, the load to submerge will vary only when there is a change in the density of the seawater.

10.2.5 Normal Fuel–Oil Tanks. Fuel–oil storage tanks are fitted with a seawater-compensating system so that they are always full of oil or seawater.

10.2.6 Main Ballast Tanks. Main ballast tanks are tanks that are flooded to submerge and blown to surface. They are fitted with vents at the top, which are opened to flood the tanks, flood openings at the bottom, and air connections for blowing.

10.2.7 Fuel Ballast Tanks. Fuel ballast tanks are tanks that may be rigged either as normal fuel–oil tanks or as main ballast tanks. When used for fuel, they are compensating tanks and are handled in the same manner as the normal fuel tanks. After the oil in the fuel ballast tanks has been burned, they may be converted to serve as main ballast tanks, and thereafter flooded

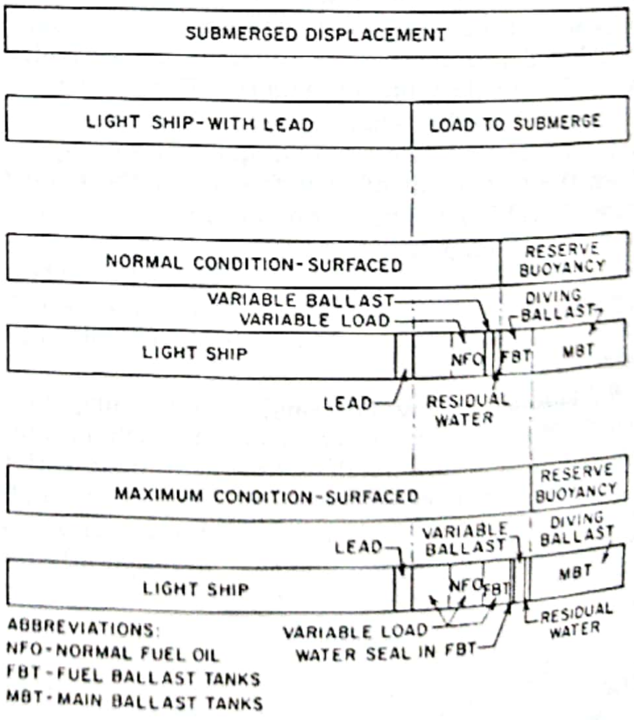


Fig. 63 Weights, diesel-powered submarine.

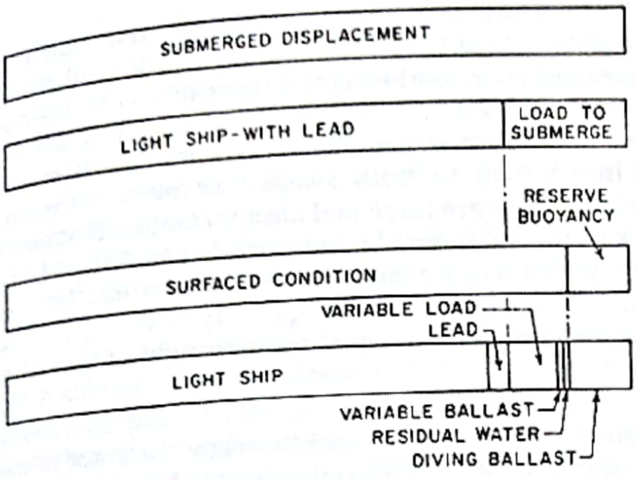


Fig. 64 Weights, nuclear-powered submarine.

upon submerging and blown upon surfacing. Conversion to main ballast tanks reduces the surface displacement and increases the reserve buoyancy until the ship is refueled. Fuel ballast tanks are not fitted on nuclear-powered submarines because of the small amount of fuel oil.

10.2.8 Residual Water. Residual water is the water in main ballast tanks and fuel ballast tanks, located below the top of the flood opening, which cannot be blown upon surfacing.

10.2.9 Water Seal in Fuel Ballast Tanks. The water seal in fuel ballast tanks is the layer of water above the top of the flood opening and below the bottom of the compensating water pipe which is maintained when the fuel ballast tanks are serving as normal fuel–oil tanks to prevent spilling of oil through the flood openings as the ship rolls. When the tank is nominally full of fuel, its contents, starting from the top, consist of fuel, water seal, and residual water.

10.2.10 Diving Ballast. Diving ballast is the term applied to the water that is admitted to the ship upon diving and blown to bring the ship to the surface. When the fuel ballast tanks are used for fuel, the diving ballast is equal to the capacity of the main ballast tanks above the residual water. When fuel ballast tanks are rigged for main ballast, the diving ballast is equal to the capacity of the main ballast tanks and the fuel ballast tanks above the residual water. Some submarines have a tank near amidships designated as safety tank, which is blown upon surfacing and is considered to be a part of the diving ballast. The safety tank may be only partly filled in the submerged condition when the ship is heavily loaded. The safety tank, when installed, is intended to be equal in volume and with about the same location as the topside conning area and may be blown while the submarine is submerged to regain buoyancy in case of topside damage.

10.2.11 Normal Condition—Surfaced. This is the condition of the displacement of the ship on the surface when fuel ballast tanks are rigged as main ballast tanks.

10.2.12 Maximum Condition—Surfaced. This is the condition of the displacement of the ship on the surface when fuel ballast tanks are rigged as normal fuel oil tanks.

10.2.13 Reserve Buoyancy. This is the condition of the displacement of the volume of the envelope of the ship above the waterline in the surfaced condition, minus any free-flooding spaces.

10.2.14 Variable Load. Variable load includes such items as personnel and their effects, missiles, torpedoes, provisions, stores, cargo, passengers, potable water, reserve feedwater, battery water, reserve reactor coolant, lubricating oil, oxygen, reserve hydraulic oil, contents of sanitary tanks and hovering tanks, and fuel oil. The variable load in the normal and maximum conditions is identical except that the oil in the fuel ballast tanks is included in the maximum condition.

10.2.15 Variable Ballast. Variable ballast is seawater ballast that is adjusted continuously at sea to compensate for changes in variable load or in seawater density. Variable water ballast is carried in forward and after tanks called trim tanks and in midship tanks called auxiliary tanks to permit adjustment of the longitudinal moment as well as the weight. Some diesel-powered boats have variable fuel–oil tanks that are noncompensating tanks sized so that the weight of oil that they carry is approximately equal to the increase in weight that occurs when the oil in the compensating tanks is replaced by seawater. Burning oil from the variable fuel oil tanks so that the percentage remaining in these tanks is the same as the percentage remaining in the compensating tanks will tend to keep the weight of the contents of all oil tanks nearly constant. Variable fuel–oil tanks are piped so that oil may be transferred between them and the compensating tanks. This transfer involves an increase or decrease in the ship's weight as the compensating water is drawn or expelled from the normal fuel oil tanks. Because of this capability, they are considered as part of the variable ballast rather than part of the variable load.

10.3 Relationships Between Items of Weight. As conditions for submerged equilibrium, each of the bars in Figs. 63 and 64 must represent the same weight and each must have its CG in the same longitudinal position. Two other equations are indicated by the vertical lines in Figs. 63 and 64. First, the reserve buoyancy is equal to the diving ballast, and the longitudinal positions of their centroids must coincide. Also, the load to submerge (the difference between the submerged displacement and the lightship with lead) is equal to and has the same longitudinal CG as the sum of the variable load, variable ballast, residual water and diving ballast, and, in the maximum condition, the water seal in the fuel ballast tanks.

These necessary equalities are achieved by variations in weight and longitudinal position of the CG of the lead ballast and the variable ballast. To conserve space, the variable ballast tanks are sized to accommodate only the probable variation in the variable load plus the variation in the submerged displacement caused by changes in seawater density. Lead ballast, since it occupies less space per ton, is used for the required adjustment beyond the capacity of the variable ballast tanks. In general, changes in lead are made in the shipyard to compensate for changes in the lightship weight or in the volume of the submerged displacement, while the variable ballast is used to compensate for changes that occur at sea.

10.4 Diving Trim. A submarine on the surface at sea is normally kept in diving trim, which means that the weights aboard are adjusted so that completion of flooding of the main ballast tanks, and any fuel ballast tanks rigged as main ballast tanks, will submerge the ship in a condition of equilibrium, with the ship's weight equal to the submerged displacement and the CG in the same longitudinal position as the center of buoyancy.

It can be seen from Fig. 63 that the weight and longitudinal moment of the surfaced ship in diving trim must be equal to the difference between the figures for the submerged displacement and those for the reserve buoyancy, and that the reserve buoyancy corresponds, in weight and center, to the diving ballast. Since the volume and moment of both the submerged displacement and the diving ballast depend only on the configuration of the ship, the surface drafts in diving trim, in either the normal or the maximum condition, are determined by the geometry of the hull.

Diving trim is maintained at sea by adjustment of water in the variable ballast tanks. Where variable fuel tanks are fitted, the oil in these tanks may also be adjusted. While the submarine is submerged at very low speeds, variable ballast may be admitted, discharged, or transferred longitudinally until any fore-and-aft inclination is eliminated and any appreciable tendency to rise or settle disappears. Between such experimental adjustments, the proper quantity and disposition of variable ballast is maintained by recording all changes in weight such as the replacement of fuel by seawater, ejection of trash or blowing of sanitary tanks, and making compensating changes in the variable ballast.

In addition to such gradual or minor changes in weight, there are large and abrupt changes that may occur in the submerged condition, due to firing of weapons, which require immediate compensation. This is accomplished by admitting a quantity of water, as part of the firing operation, equal to the weight of the weapon ejected.

The moment diagram, illustrated in Fig. 65 is a convenience in finding the change in weight that must be made in the variable ballast to compensate for a change in the variable load. If a weight, w, is added at some point, P, along the ship's length, reading the scales directly below point P will indicate the percentage of the weight, w, to be removed from the after trim and the auxiliaries, or from each of the two trim tanks, to compensate for the added weight. In this diagram, which is usually plotted below an inboard profile of the ship to which it applies, points A, B, and C are located, respectively, at the locations of the centroids of the after trim, auxiliaries, and the forward trim tanks. The scales are constructed by dividing the distances between A and B, B and C, and A and C into 100 equal divisions.

As an example of the use of the moment diagram, if 1000 kg is added at point P in Fig. 65, there will be no change in the weight or in the longitudinal position of the CG of the ship if either:

1. Two hundred and ninety kg of water are blown from the forward trim tank and 710 kg are blown from the after trim tank, or
2. Five hundred and thirty kg are blown from the auxiliary tanks and 470 kg are blown from the after trim tank.

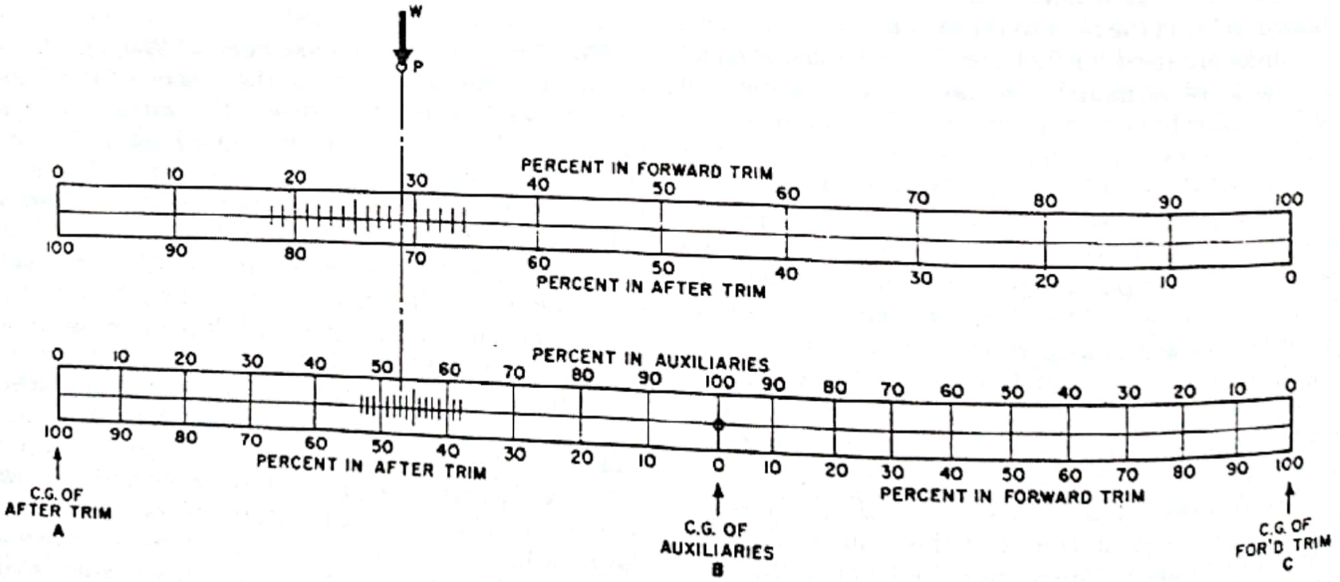


Fig. 65 Moment diagram for submarine.

10.5 Equilibrium Conditions. Since the variable ballast must be adjusted to compensate for changes in seawater density and for changes in the variable load, it is necessary to evaluate the magnitude of probable changes in both the weight and the longitudinal moment of these two items in order to select the proper size for the variable ballast tanks.

To ensure that diving trim can be achieved with any possible variation in seawater density and variable load, it would be necessary to develop the lightest possible condition in the heaviest seawater, the heaviest possible condition in the lightest water, and conditions with maximum longitudinal moments in each direction in both heavy and light seawater and to make the variable ballast tanks large enough to compensate for these changes. This would result in very large variable ballast tanks on a ship having a limited amount of space. By using judgment to eliminate improbable extreme conditions, the variable ballast tanks can be held to a reasonable size.

In displacement calculations for surface ships, the seawater-specific volume is assumed to be 0.975 m^3 per ton, and the normal variations from this figure are negligible, since they would produce only a small change in draft. A small change in the displacement of a submerged submarine, such as 10 tons, would result in an unacceptable imbalance between weight and buoyancy. Since 10 tons is a small percentage of the submerged displacement, only a small change in the density of the seawater is required to produce such an unbalance.

The specific volume of seawater has been found to vary from 0.981 to 0.971 m^3 per ton. The extreme variation in variable ballast to compensate for this effect would occur if the ship were to dive in light water, filling the main ballast and fuel ballast tanks, and then pass, submerged, into heavy water. It is customary to assume that this extreme, or the opposite, will not occur, and that the diving ballast is of the same density as that in which the submarine is operating. Under this assumption, the quantity of variable ballast needed for variation in seawater density is equal to the submerged displacement less the diving ballast, in cubic meters, multiplied by the change in density. As an example, if the submerged displacement is 4000 t and the diving ballast 500 t, the quantity of variable ballast needed to counteract this effect would be:

$$(4000-500)t \times 0.975 \times \left(\frac{1.0}{0.971}-\frac{1.0}{0.981}\right)$$
$$=3500 \times 0.975 \times (1.03-1.02)$$
$$=3500 \times 0.975 \times 0.01 = 34t$$

For the purpose of studying the additional variation in variable ballast necessary to compensate for changes in the variable load, calculations are made for a series of *equilibrium conditions* representing heavy loads in light water, light loads in heavy water, and heavy forward and heavy aft loadings in both light and heavy water. In calculating the loads aboard for any particular condition, judgment and familiarity with operating procedures are necessary in deciding on the quantities of the various items of variable load if very large variable ballast tanks are to be avoided.

The *heavy forward* and *heavy aft* conditions are not necessarily heavy. The term heavy forward, for example, means that loads in the forward end are heavy while those aft are light. In a ship that carries most of the variable load forward, the heavy aft condition might be quite light. In the heavy aft condition, the quantities of torpedoes and dry cargo, for example, would be assumed to be zero in the forward portion of the ship while a full load of such items would be assumed aft. As in the ease of the heavy and light conditions, it is advisable to investigate two heavy forward and two heavy aft conditions: one with a large percentage of fuel aboard in which only the oil in the fuel ballast tanks at the heavy end has been burned and a condition occurring later when all oil in the fuel ballast tanks and in the normal fuel–oil tanks at the heavy end has been burned. Since the heavy forward and heavy aft conditions are not necessarily either heavy or light, calculations should be made for both heavy and light seawater.

The final result of the equilibrium-condition calculations is the weight and longitudinal moment of the *variable ballast to balance*, which is the variable ballast required under the assumed loading and seawater density to bring the ship to diving trim on the surface and to submerged equilibrium after diving.

As shown in Figs. 63 and 64, the variable ballast to balance can be established by subtracting the summation of weight and longitudinal moment of the variable load from the figures for the load to submerge. Figures 63 and 64 also show the load to submerge may be found by deducting the weight and longitudinal moment of the lightship, with lead, from the figures for the submerged displacement. Two sets of values for the load to submerge are found by using figures for the submerged displacement at both 0.981 and 0.971 m^3/t. The load to submerge in light water is used for the heavy conditions, the figures for heavy water used for the light conditions, and both are used for the heavy forward and heavy aft conditions. Two summations of variable load are required for the heavy forward and heavy aft conditions, so that the density of the diving ballast will correspond, in each case, to that used for the submerged displacement.

10.6 The Equilibrium Polygon. The equilibrium polygon of a typical diesel-powered submarine, illustrated in Fig. 66, is a device for presenting graphically the envelope of variation in weight and longitudinal moment which can be obtained by adjusting the variable ballast. In Fig. 66, the weight of variable ballast is plotted vertically and the longitudinal moment, about the transverse reference plane used for the equilibrium conditions, is plotted horizontally. Each side of the polygon represents the effect of filling one of the variable ballast tanks. The polygon is constructed by adding, algebraically and successively, the weights and moments of each of the variable ballast tanks, starting with the forwardmost tank and proceeding aft, then repeating the process starting with the aftermost and proceeding forward. Each summation is plotted as in Fig. 66, where line *OA* represents the weight and moment developed as the forward trim tank is filled, line *AB* the effect of filling the forward variable fuel oil tank after the forward trim tank has been filled, and so forth until point *E*, representing the weight and moment of all the variable ballast tanks, is reached. The same point *E* is reached by a different route by plotting the various stages of the summation starting with the aftermost tank and proceeding forward.

The weight in each of the variable ballast tanks is taken to be equal to the net capacity of the tank at specific volume of 0.975 m^3 per ton. This volume is applied to the variable fuel tanks, even though they contain oil, because the transfer of 0.975 m^3 of oil from a variable fuel tank to a normal fuel tank would force 0.975 m^3 seawater, or 1 ton, overboard. The change in weight is assumed to occur at the location of the variable fuel tank, although there will also be a small change at the indeterminate location of the normal fuel–oil tank to which the oil is transferred.

The exterior broken line in Fig. 66 shows the effect of considering the *negative tank* as part of the variable ballast. This tank, located forward of the center of buoyancy and normally empty in the surfaced and submerged conditions, is customarily filled just prior to diving in order to expedite the operation. This causes the weight of the ship to exceed the submerged displacement by a few tons and produces a down angle on the ship, both of which are favorable to rapid submerging. The negative tank is blown when the ship reaches the ordered depth, restoring equilibrium. If necessary to meet very light equilibrium conditions, the negative tank may be treated as part of the variable ballast, if the loss of the advantage of its normal function in the light condition is accepted.

The variable ballast can be adjusted so that its weight and moment correspond to the coordinates of any point within the polygon. Point *P* in Fig. 66, for example, can be reached by filling the after trim tank, moving from *O* to *I*; part of the after variable fuel tank, moving from *I* to *S*; then partially filling the auxiliaries, forward variable fuel tank, and the forward trim tank. Line *SR* is parallel to and not longer than *HG*, *RQ* is parallel to and not longer than *GF*, and *QP* is parallel to and not longer than *FE*. This is only one of many ways in which point *P* can be reached.

Fig. 67 is the polygon of Fig. 66, with the weight and moment of the variable ballast to balance for the various equilibrium conditions plotted. It is immediately apparent from Fig. 67 that the ship cannot be brought to submerged equilibrium in Condition Heavy No. 2 in light seawater, and that all other conditions can be met without the use of the negative tank, although there is but little margin in the ease of Light No. 2.

10.7 Adjustment of Lead and Variable Ballast Tankage. Under the conditions shown in Fig. 67, it is apparent from Figs. 63 and 64 that, if some lead ballast were removed, the amount of variable ballast required would be increased, and Condition Heavy No. 2 in Fig. 67 would move upward into the polygon. Also, if some lead were shifted aft with no change in the total amount, this point would move horizontally to the right into the polygon. All other points in Fig. 67 representing equilibrium conditions would, in either case, move the same distance and in the same direction. This shows that all points may be moved, as if they were plotted on a separate

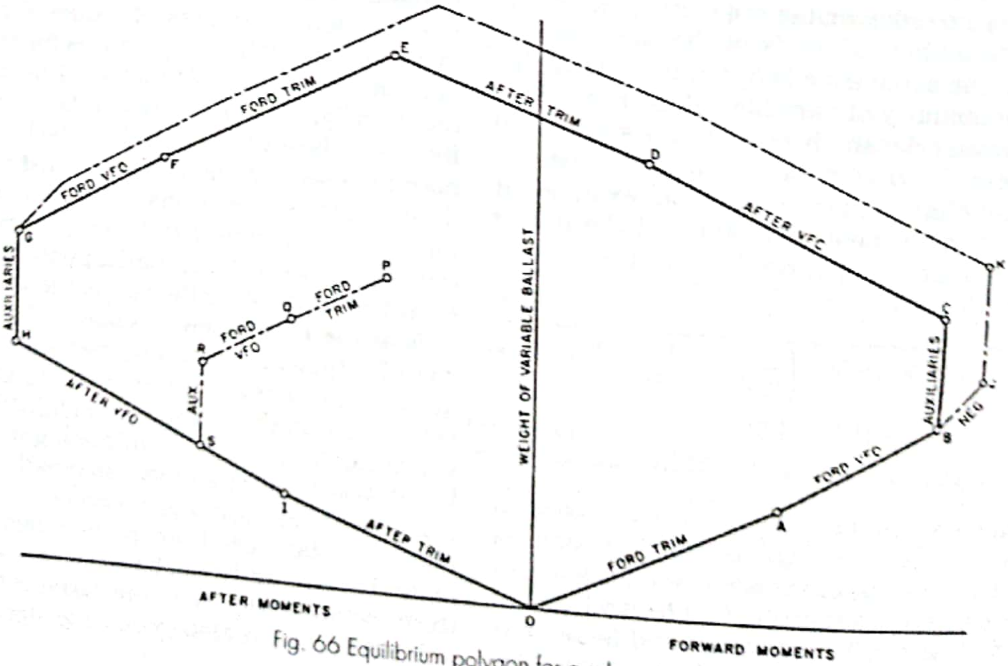


Fig. 66 Equilibrium polygon for a submarine.

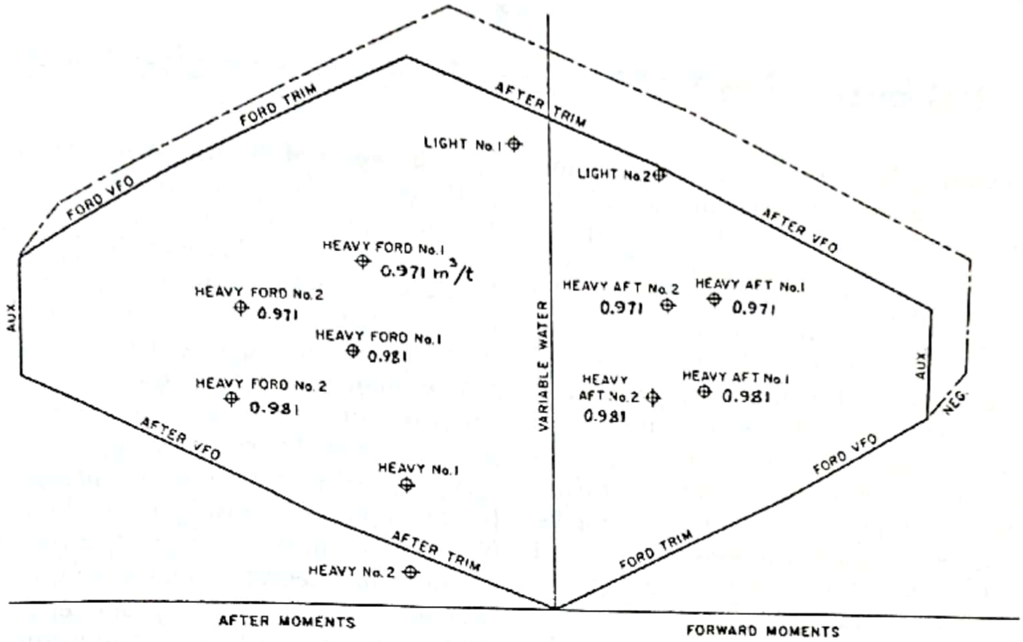


Fig. 67 Equilibrium polygon for Fig. 66, with required weight and moment plotted for several loading conditions.

piece of paper, either fore and aft or up and down, or a combination of both, by adjustment of the lead ballast. There may be, of course, some physical limitation on the adjustment of lead, or its removal may be precluded by considerations of transverse stability.

In the case shown in Fig. 67, it is apparent that the spread of the points representing the equilibrium conditions is beyond the capacity of the variable water and variable fuel tanks, but that the constellation of points can be embraced by the polygon that includes the effect of the negative tank. If the ship were already built, the loss of complete effectiveness of the negative tank in diving in the light condition in heavy water would probably be accepted and Light No. 2 allowed to move into the area representing the effect of the negative tank. Otherwise, it would be prudent to consider an increase in the size of the polygon. In this situation, the polygon is useful in deciding which tank or tanks should be enlarged. It is apparent from Fig. 67 that no improvement would result from increasing the capacity of the after variable fuel tank or the after trim tank, since this would only extend the polygon to the left. The greatest gain, per ton increase in capacity, would be obtained by increasing the size of the auxiliary tanks, but if this were not feasible, increasing either the forward trim or the forward variable fuel tank would be effective.

10.8 Stability in Depth. While the forces of weight and buoyancy can be brought very nearly to equilibrium when a submarine is submerged, most submarines have no inherent stability with respect to depth since, as the ship settles or rises, no force is generated to return the ship to the original level. A situation may exist in which the water at greater depths may be appreciably denser than that near the surface because of differences in temperature and salinity, which will enable the submarine to rest on the interface if its weight is greater than its displacement in the less dense water but less than its displacement in the denser water. Otherwise, unless some force is applied, as by the planes or a hovering system, most submarines would eventually either rise to the surface or settle to the bottom.

On the normal submarine, the pressure of the seawater on the hull tends to produce an unstable condition. The loss of buoyancy due to compression of the hull as the ship settles exceeds the gain in buoyancy due to compression of the seawater and the resulting slight increase in its density. The net result is that buoyancy is decreased as the ship settles and increased as the ship rises. The effect of sea pressure would be aggravated if there were a partially filled tank open to the sea, since the air therein would expand and compress readily with changes in depth, expelling water when the ship was rising or admitting water settling.

On some very rigid hulls, the effect is reversed, since the effect of compression of the hull is less than the effect of the compression of the seawater in increasing the water density. This results in a small gain in buoyancy as the ship settles, a small loss when it rises, and hence a minor stabilizing effect.

11

The Trim Dive

11.1 Basic Principles. The trim dive is an experimental determination of the weight and longitudinal moment of the load to submerge, as defined in Section 10.

Theoretically, the *load to submerge* could be obtained, as illustrated in Figs. 63 and 64 by deducting the lightship with lead, as determined from the inclining experiment, from the calculated figures for the submerged displacement. The submerged displacement, however, cannot be calculated accurately because of numerous topside appendages. Also, the load to submerge, determined in this manner, would represent a small difference between two large quantities, and therefore be subjected to a larger error than if it were determined directly. It is therefore customary to find the load to submerge experimentally by an inventory of all weights aboard that comprise the load to submerge, taken while the ship is in submerged equilibrium.

The load to submerge is used as the basis for calculating the variable ballast to balance in the various equilibrium conditions, which, in turn, determines the optimum weight and disposition of the lead ballast.

11.2 Conducting the Trim Dive. The ship is completely submerged in an area that is free from strong currents and sharp density gradients. The variable ballast is carefully adjusted to bring the ship to submerged equilibrium. The ship is held at rest long enough to ensure that there is no fore and aft inclination and no appreciable tendency to rise or settle.

While the ship is in submerged equilibrium, a sample of seawater is taken, preferably from a circulating system in operation, and the density determined.

An inventory is taken of the weight and longitudinal moment of all items aboard (other than lead ballast) that are not part of the lightship weight. As in the case of the inclining experiment, this inventory must be based on a comprehensive definition of the lightship condition. The total weight and moment resulting from this inventory are the load to submerge and its longitudinal moment at the seawater density observed concurrently with the inventory.

11.3 Report of the Trim Dive. The calculations made in the report of the trim dive involve converting the load to submerge at the density of the seawater in which the ship was submerged to its values at specific volumes of 0.981, 0.975, and 0.971 m^3/t. As mentioned in Section 10, these values represent the variation in seawater-specific volume and are used in the equilibrium conditions, where small variations in specific volume are important. The value of 0.975 m^3/t is used in stability calculations, as in the case of surface ships.

When the inclining experiment and the trim dive have been completed, the weights and longitudinal moments of the lightship with lead and of the load to submerge are known. Theoretically, the sum of these two items should correspond to the volumetric calculations for the submerged displacement, but minor discrepancies are to be expected due to the inaccuracies involved in each of the three items. It is customary to regard the submerged displacement from the inclining experiment and trim dive as being more accurate than that obtained from the volumetric calculations.

The values of the load to submerge at the various seawater-specific volumes are obtained as follows:

1. The submerged displacement and its longitudinal moment at the time of the trim dive are obtained by adding the weights and moments of the lightship with lead from the inclining experiment and the load to submerge from the trim dive.
2. The submerged displacement and its longitudinal moment at 0.981, 0.975, or 0.971 m^3/t are found by multiplying the weight and moment obtained in step 1 by the ratios of 0.981, 0.975, and 0.971 m^3/t to the specific volume of the outside seawater.
3. The load to submerge and its longitudinal moment at specific volume of 0.981, 0.975, and 0.971 m^3/t are obtained by subtracting the figures for the lightship with lead from the submerged displacement at those specific volumes.