5
BUOYANCY AND STABILITY

A. BUOYANCY

5A1. Introduction. Buoyancy is generally understood to be that property of a body that enables it to float on the surface of a liquid or in a fluid. While such a definition is true, it does not fully define the term. Buoyancy, considered in connection with submarines, is the upward force asserted on an immersed or floating body by the supporting fluid. This conception of the term conveys the idea that *volume*, alone, determines buoyancy, and that the upward force exerted on the immersed or floating body equals the weight of the fluid which it displaces. This idea is illustrated by the diagrams in Figure 5-1.

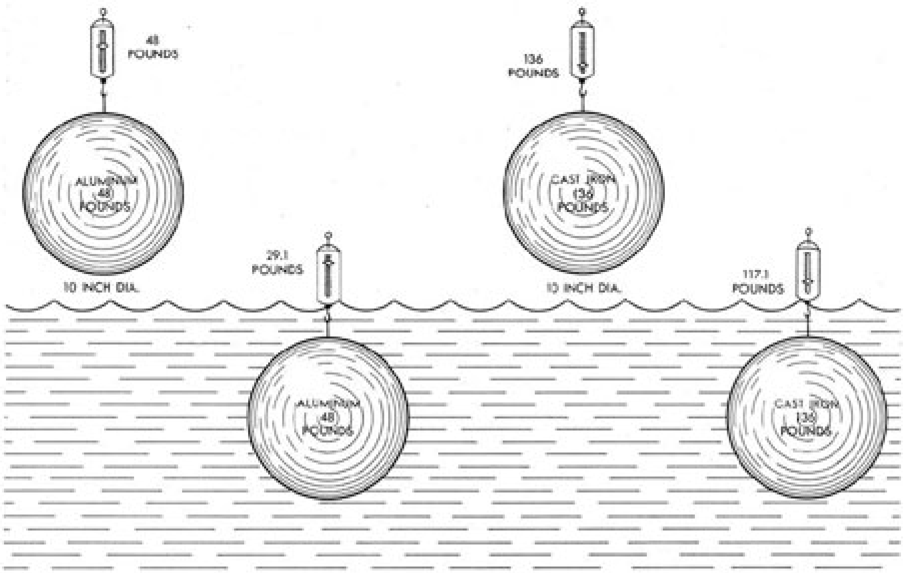

Figure 5-1. Buoyancy depends on volume.

A sphere of aluminum and one of cast iron, each 10 inches in diameter, are weighed in air and then immersed in water. The aluminum sphere weighs approximately 48 pounds and the cast iron sphere, 136 pounds. If the spheres are lowered into the water, the scale reads 29.1 pounds for the aluminum, and 117 pounds for the cast iron. The differences in weight, 48 - 29.1 = 18.9 and 136 - 117.1 = 18.9, are the same, showing that the buoyancy, or upward force of the displaced water, is the same in both cases and is independent of the weight of the immersed body.

The buoyancy of a submarine is also dependent on the volume of the displaced water and it is controlled by varying the volume of displacement as illustrated in Figure 5-2.

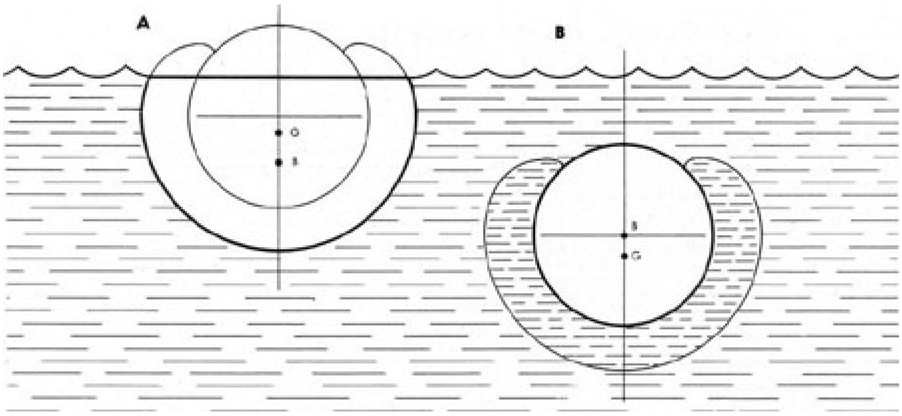

Figure 5-2. Volume of displacement is changed.

Diagram A, Figure 5-2, represents a submarine on the surface. Its main ballast tanks are filled with air. The displacement water, represented by the area within the heavy line, equals the weight of the submarine.

Diagram B, Figure 5-2, represents a submerged submarine. Water has been admitted to the main ballast tanks, expelling the air. The displaced water is now represented by the area within the heavy circle. The over-all weight of the submarine is not changed, but the submarine may be submerged because the volume of displaced water has been reduced and the weight of the displaced water is now the same as or less than the weight of the submarine.

5A2. Center of buoyancy. The *center of buoyancy* is the center of gravity of the displaced water. It lies at the geometric center of volume of the displaced water. The center of buoyancy should not be confused with the center of gravity of the immersed, or floating, body. These two centers are indicated as *B* and *G,* respectively, on the sketches in Figure 5-2.

5A3. States of buoyancy. By definition, buoyancy is the upward force exerted on a floating, or immersed, body and is independent of the weight of the body. The state of buoyancy refers to the ratio between the weight of the body and the weight of the displaced fluid. In the case of submarines, the displaced fluid is sea water. Three *states of buoyancy* are considered: 1) positive buoyancy, 2) neutral buoyancy, and 3) negative buoyancy.

1. *Positive buoyancy* exists when the weight of the body is less than the weight of an equal volume of the displaced fluid.

2. *Neutral buoyancy* exists when the weight of the body is equal to the weight of an equal volume of the displaced fluid. A body in this state remains suspended, neither rising nor sinking, unless acted upon by an outside force.

While this condition might be attained in a laboratory, it is doubtful that it is ever obtained exactly in a submarine. Nevertheless, the condition is approached and any discrepancy is counteracted by the diving planes; the ship is then considered to be in a state of neutral buoyancy.

3. *Negative buoyancy* exists when the weight of the body is greater than the weight of an equal volume of the displaced fluid and the body sinks.

Theoretically, a submarine is designed with its main ballast tanks of such volume that when they are flooded, the ship is in the state of neutral buoyancy. Negative buoyancy is gained by flooding the negative tank.

B. STABILITY

5B1. Stability. Stability is that property of a body that causes it, when disturbed from a condition of equilibrium, to develop forces, or moments, that tend to restore the body to its original condition. Because stability is a state of equilibrium, this term should be defined.

5B2. Equilibrium. Equilibrium is a state of balance between opposing forces and may exist in three states: (1) stable, 2) neutral, and 3) unstable.

1. Stable equilibrium is that property of a body that causes it, when disturbed from a condition of equilibrium, to develop forces, or moments, that tend to restore it to its original condition. When a floating body is in stable equilibrium, its center of gravity and its center of buoyancy are in the same vertical line.

2. Neutral equilibrium exists when a body remains in its displaced position.

3. Unstable equilibrium exists when a body tends to continue movement after a slight displacement.

These three states are illustrated in Figure 5-3.

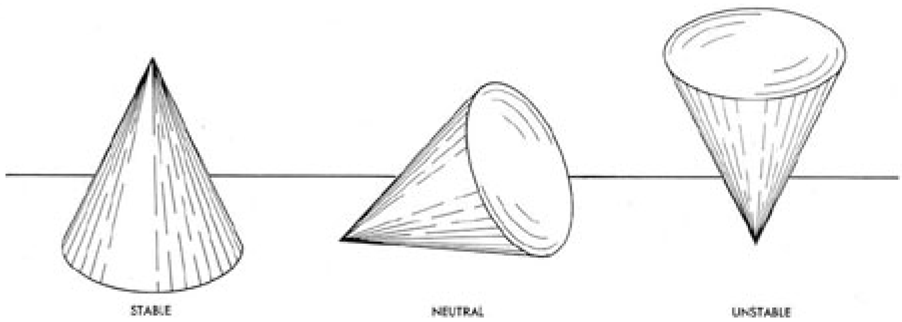

Figure 5-3. States of equilibrium

A cone resting on its base may be tipped in any direction, within limits, and will return to is original position when released.

A cone lying on its side may be rolled on its surface and will remain in its displaced position. A cone may be balanced on its point and remain in equilibrium but, when disturbed, will increase its displacement.

The two conditions, buoyancy and stability, are so closely related and interdependent when considered in connection with submarines that they must be discussed together.

All floating bodies, including both surface ships and submarines, are subject to the same natural forces, and these forces in all cases follow the same physical laws. There is a difference, however, between the stability of surface ships and the stability of submarines. Because submarines are special cases of floating bodies, their stability requires a special application of these laws.

Another term, *metacenter,* needs to be understood before proceeding with the discussion of stability.

5B3. Metacenter. Metacenter is the point of intersection of a vertical line through the center of buoyancy of a floating body and a vertical line through the new center of buoyancy, as shown in the diagrams in Figure 5-4.

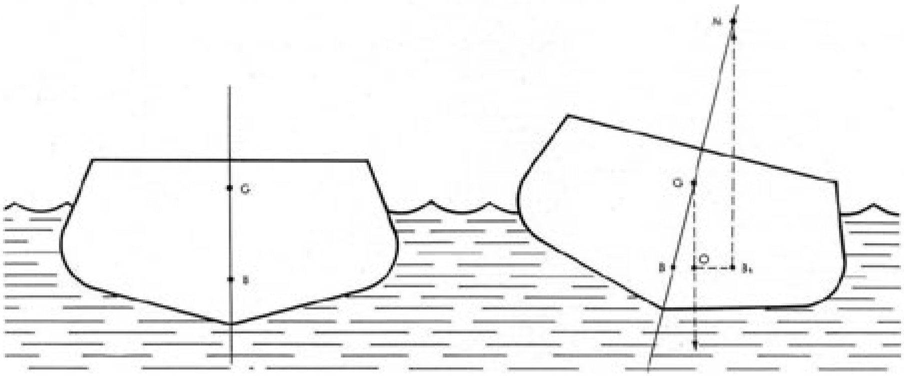

Figure 5-4. The metacenter.

When a vessel is tipped as shown, the center of buoyancy moves from *B* to *B1*, because the volume of displaced water at the left of *G* has been decreased while the volume of displaced water to the right is increased. The center of buoyancy, being at the center of gravity of the displaced water, moves to point *B1*, and a vertical line through this point passes *G* and intersects the original vertical at *M*. The distance *GM* is known as the *metacentric height.* This illustrates the fundamental law of stability. When *M* is above *G*, the metacentric height is positive and the vessel is stable because a moment arm, *OB1*, has been set up which tends to return the vessel to its original position. It is obvious that if *M* is located below *G*, the moment arm would tend to increase the inclination. In this case the metacentric height is negative and the vessel would be unstable.

When on the surface, a submarine presents much the same problem in stability as a surface ship. However, some differences are apparent as may be seen in the diagrams in Figure 5-5.

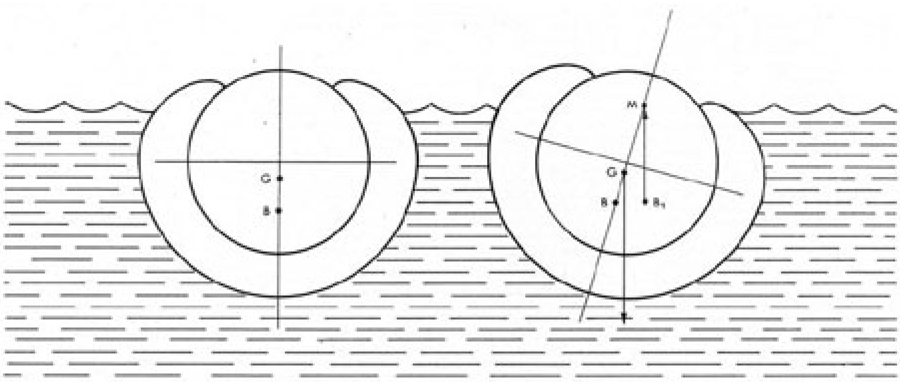

Figure 5-5. A submarine on the surface.

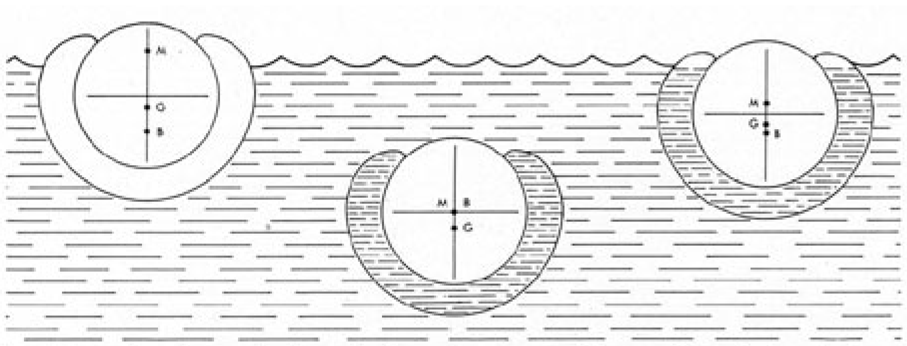

Figure 5-6. Change of center of buoyancy and metacenter during submergence.

The three points, *B, G,* and *M,* are much closer together than is the case with is a point during submergence or surfacing when *B* coincides with *G* and *GM* becomes zero or perhaps a negative surface ships. When a submarine is submerged, these significant points are arranged much differently.

The center of gravity of the submarine, *G,* remains fixed slightly below the centerline of the boat while *B* and *M* approach each other, *B* rising and passing *G*, until at complete submergence *B* and *M* are at a common point. These changes are shown diagrammatically in Figure 5-6.

On the surface the three points, *B, M,* and *G*, are in the same relative positions as for surface ships. As the ballast tanks fill, the displacement becomes less with the consequent rising of *B* and lowering of *M*. There quantity. During a normal dive, this point is passed so quickly that there is no time for the boat to take a list. When the ballast tanks are fully flooded, *B* rises to the normal center of buoyancy of the pressure hull, and stability is regained with *G* below *B.*

Just why these centers change so radically may be made more readily apparent by an illustration with rectangular sections. The diagrams in Figure 5-7 represent a rectangular closed chamber, so weighted at *G* that it will sink in water. The area surrounding it at the sides and bottom represents air chambers.

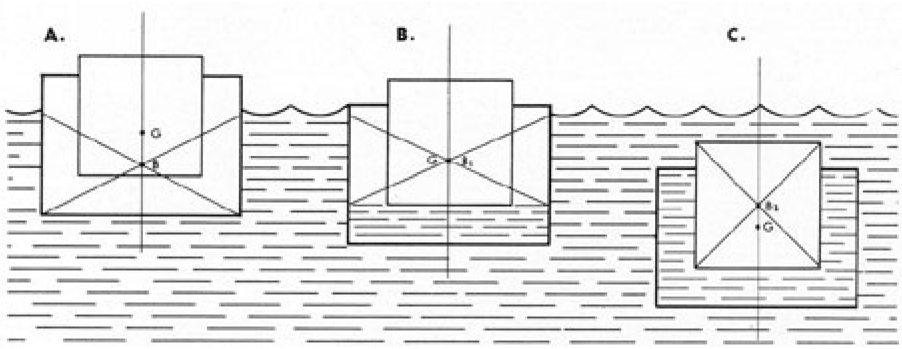

Figure 5-7. The center of buoyancy shifts.

At A, the vessel is floating with all water excluded from the tank surrounding the chamber. The center of gravity is at *G* and the center of buoyancy, *B,* is found by intersecting diagonals of the displacement.

At B, water has been admitted to the lower section of the tank. Using the diagonals as before, it is seen that the center of buoyancy, *B,* is now coincident with *G* and the unit is unstable.

At C, the surrounding tank is flooded and the unit is submerged. The center of buoyancy is at *B2*, the intersection of the diagonals of the displaced water. The unit is stable, the center of buoyancy and the center of gravity are in the same vertical line. Any rotational movement about the center of buoyancy *B2* immediately sets up a restoring moment arm.

shape below the waterline all affect stability.

It is an axiom that high freeboard and flare assure good righting arms and increase stability, and low freeboard and "tumble home," or inward slope, give small righting arms and less stability. The diagrams in Figure 5-8 show why this is true.

Diagram A represents a cylindrical vessel with its center of gravity at the center of the body and so weighted that it floats on its centerline. Its center of buoyancy is at the center of gravity of the displaced water.

It is at once apparent that this vessel is not in stable equilibrium. *G* and *B* will remain in the same position regardless of rotation of the body. As no righting arms are set up, the vessel will not return to its original position.

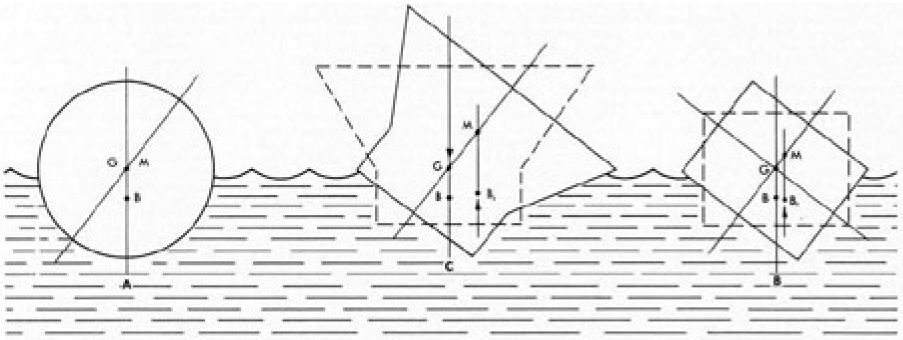

Figure 5-8. The effect of shape and freeboard on stability.

When surfacing, with the water ballast being ejected comparatively slowly by the low-pressure blowers, *GM* may become negative and a list may occur. As a corrective measure, if a list should occur, certain main ballast tanks are provided with separate low-pressure blow lines for the port and starboard sections. Lever-operated, list control valves are installed so that air to the tanks on the high side may be restricted and more air delivered to the low side.

5B4. Transverse stability. The stability of any vessel on the surface depends upon two things: 1) the position of the center of gravity, and 2) the shape of the vessel. The shape above the waterline, the freeboard, and the

Diagram B represents a vessel of equal volume and the same waterline. Its center of gravity is at the center of volume, and the center of buoyancy is at the center of gravity of the displaced water. When this vessel is inclined about its center of gravity, the effect of change of shape is noticeable. The volume of displaced water at the left of *G* is decreased and the displacement at the right is increased. The center of buoyancy moves to the right, the metacenter, *M,* is above *G,* and the force coupled B_1G, tends to right the vessel.

In diagram C the vessel is flared from the waterline and its freeboard increased. When this vessel is inclined, the added

displacement of the flare is added to that resulting from the shape of the underwater section, and the center of buoyancy shifts about four times as far, raising the metacenter and providing a stronger righting arm.

The submarine has the worst possible shape, little freeboard and extreme tumble home. For this reason, every effort is made to keep the center of gravity as low as possible. The storage batteries, weighing approximately 1 ton per cell, and all heavy machinery are set as low as possible, but the superstructure, deck equipment, and conning tower total a considerably high weight. Because of the difficulty of getting the normal center of gravity low enough, submarines usually carry lead ballast along the keel.

than that resulting from the shorter transverse axis; consequently, the center of buoyancy moves a greater distance. In the ship illustrated, the movement of the center of buoyancy to the right is approximately 23 feet, giving a surface metacentric height of 370 feet. Because of the shorter transverse axis, the transverse metacentric height is only 1 1/2 feet.

When a submarine submerges, however, the water plane disappears and the metacenter comes down to the center of buoyancy. This is because the forces on a submerged body act as if the body is suspended from its center of buoyancy. Being submerged, the volume of displaced water on each side of the center of buoyancy remains constant, regardless of the angular displacement of the axis. As the center of rotation

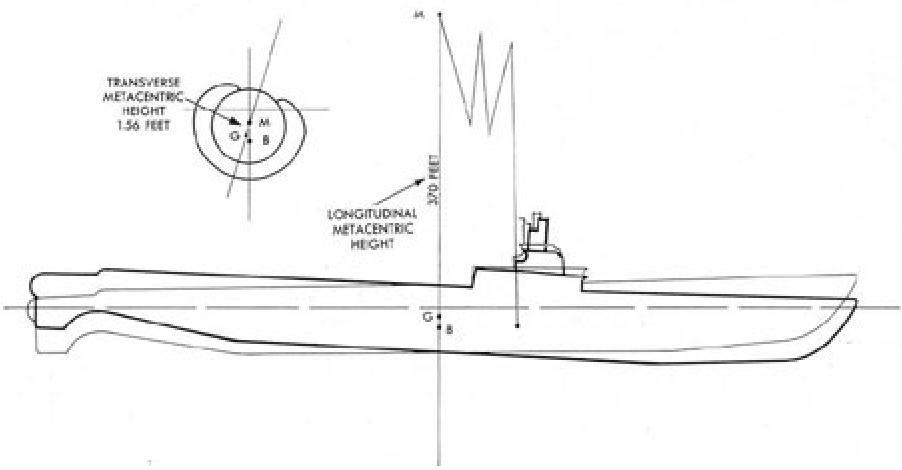

Figure 5-9. Stability increases with length of waterline.

5B5. Longitudinal stability. The longitudinal stability of a submarine is much greater than the transverse stability. Stability in both cases depends on the relative positions of the metacenter and the center of gravity but, in this case, the metacenter is calculated with respect to the longitudinal axis.

Figure 5-9 shows why a slight angular displacement of water resulting from a slight angle of the longitudinal axis is much greater of a submerged body is at its center of buoyancy, vertical lines through this center, for any position of the body, always intersect at the same point. Thus, for a submerged body, the metacenter and center of buoyancy are coincident. This agrees with the definition of metacenter given on page 55. Therefore, the longitudinal *GM* and the transverse *GM* are the same for a submerged submarine except for the effect of free surface.

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5B6. Free surface. Free surface refers to the surface of ballast water in a partially filled tank in which water is free to move and to assume its normal surface. The adverse effect of free surface in a ballast tank may be visualized from the diagrams in Figure 5-10.

Free surfaces affect longitudinal stability more than transverse stability because of the greater moment arms involved.

Diagram A represents a tube, with closed ends, partially filled with water.

It is suspended at *B*, the exact center of its length. The center of gravity of the water is at *G*. *B* and *G* are on the same vertical line and the tube is in equilibrium. If submerged. The fuel ballast tanks are connected with the sea and the fuel is forced out at the top. Thus they are always filled either with oil or water or some proportion of each.

During submergence, when the ballast tanks are being flooded and again when they are being blown for surfacing, there is a period during which free surface exists in all main ballast tanks. To reduce the effect of this free surface the ballast space is divided by transverse bulkheads into a number of separate tanks. The effect of this division of the longitudinal ballast space is illustrated in diagram C, Figure 5-10.

Partitions are indicated in the tube, each section has its own center of gravity,

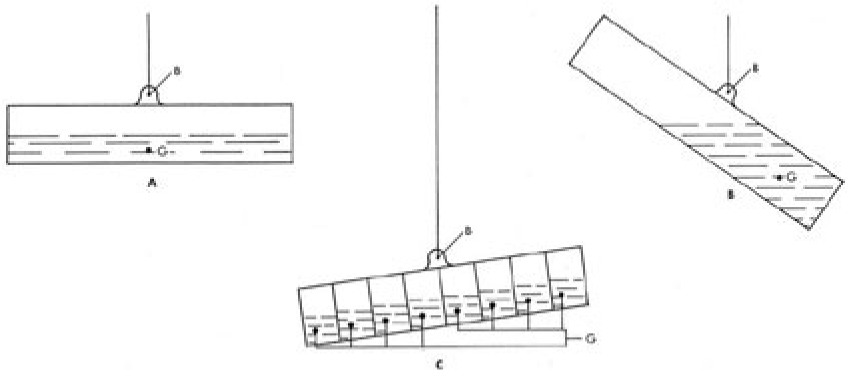

Figure 5-10. Effect of free surface on stability.

the tube is disturbed even slightly, the free surface permits the water to flow to the low end and as shown in diagram B. Any movement of the water toward either end moves the center of gravity and sets up a moment arm, increasing both the inclination and the moment arm. This continues until the water is in one end of the tube and *G* is again on the same vertical line with *B*.

If the tube is filled with water, eliminating all free surface, there can be no movement of the water, and the unit acts as a solid and remains in stable equilibrium.

Submarines are designed to eliminate, as far as possible, all free surfaces. The main ballast tanks are proportioned so that they are completely filled when the vessel is and free surface exists in all sections. As the tube is inclined, the water shifts as before but to a limited extent, and the cumulative result of the shifting of the individual centers of gravity is negligible.

In a submarine this result of a momentary free surface in the tanks is counteracted by the diving planes. However, water collecting in a flooded compartment will seriously affect both longitudinal and transverse stability.

5B7. Addition of permanent weight. The effect of adding weight to a submarine is serious, not only because it makes the vessel heavy, but also because of the consequent reduction in stability. The addition of weight

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to a surface ship causes it to sink a little lower in the water, increasing displacement and usually, stability. If the weight added is below the center of gravity, stability is further increased.

With the submarine, conditions are different, for, in order to be in readiness for submerging with the main ballast tanks empty, she must always float at the same waterline. To meet this requirement, the weight must be constant, as it is not possible to alter the capacity of the main ballast tanks or the buoyancy of the hull without structural changes. Auxiliary tanks are provided for the usual variations in weight of fuel, stores, crew, and so forth, but the addition of permanent weight would require the removal of an equal amount of permanent ballast. The added weight, if above the center of gravity, raises the original center of gravity; removal of ballast raises it still more, resulting in a reduction of the normally short righting arm and reducing stability. The addition of deck armament or any deck load should be carefully considered as to its effect on the center of gravity.

Disregard of the laws of stability will render the submarine less seaworthy and may invite disaster.

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