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Subdivision and Damage Stability

Section 1
Introduction

1.1 General. All types of ships and boats are subject to the risk of sinking if they lose their watertight integrity, whether by collision, grounding or internal accident such as an explosion. (Exceptions, of course, are vessels constructed entirely of buoyant materials and having mostly buoyant contents.) Such accidents are frequent enough in practice that some degree of protection against the effects of accidental flooding is an essential feature of the design of any water craft. The most effective protection is provided by internal subdivision by means of watertight transverse and/or longitudinal bulkheads, and by some horizontal subdivision—double bottoms in commercial ships and watertight flats in naval vessels. Such protection is by no means new, for Marco Polo, near the end of the thirteenth century, referred to watertight bulkheads in Chinese junks.

The flooding of a ship's hull can have one or the other of two principal consequences. One is loss of buoyancy and change of trim, which if unchecked will lead to sinking by foundering. The other is loss of transverse stability or build-up of such an upsetting moment that capsizing takes place. The nature and arrangement of the internal subdivision to control these effects will be discussed in this chapter. However, it will be shown that there are many uncertainties in providing adequate subdivision. First of all, the location and extent of damage to be protected against is unknown in advance. Second, the amount, type and location of cargo and liquids in the ship varies both during and between voyages. Finally, the designer cannot be sure that corrective measures that might be followed by the ship's officers in an emergency will be taken—or that hazardous steps might be adopted by mistake. Furthermore, subdivision inevitably adds to the cost of the ship and may interfere with its ability to perform its function economically. In fact, a ship so ideally compartmented as to be virtually unsinkable might be of no economic or military value whatsoever.

Consequently, the subdivision of ships inevitably involves a compromise between safety and cost. This dilemma has been partially resolved for passenger ships by the development of national and international standards of what is considered acceptable, considering the size and type of ship, the number of passengers carried, the nature of the service, etc. Hence, considerable attention will be given in this chapter to the development of such passenger ship standards and to the current status of the various standards now in effect.

It will be seen that for cargo ships subdivision standards have been minimal. However, for these vessels, the above dilemma of cost versus safety can be resolved more scientifically, provided that loss of human life can be ruled out by virtue of reliable provisions for lifesaving—with time to use them provided by some subdivision. This approach is based on probability calculations to minimize the *expected cost,* which is the sum of the extra cost of the subdivision and the so-called *failure cost,* the total value of the ship and its contents multiplied by the probability of its loss during its lifetime. This procedure has been applied to design problems of off-shore structures (Freudenthal, 1969),[1] but has not yet been standardized by regulations.

For passenger ships, where it is unrealistic to assume no risk to human life, the problem is that it is difficult to put a dollar value on a life. However, efforts have been made to evaluate statistically the levels of risk actually found in different modes of transportation and hence to draw conclusions regarding what people generally consider acceptable (W. European Conf., 1977). Furthermore, court decisions have in effect established a value for human life by the awards made in actions brought before them.

It will be shown in this chapter how a trend toward

[1] Complete references are listed at end of chapter.

probabilistic solutions is well along in the area of ship subdivision standards. A similar probabilistic approach is being applied in the field of ship structural design, as discussed in Chapter IV. The probability approach can also be extended to cover the cost of environmental damage resulting from accidents involving ships.

1.2 Historical. In the late nineteenth century, classification societies established empirical rules for the installation of bulkheads in merchant ships, primarily fore and after peak bulkheads and bulkheads separating the machinery space from cargo holds. These classification society provisions were not based on any specific degree of floodability (and are not today).

In the late nineteenth and early twentieth century the major maritime nations were studying means for determining the capability of ships to resist flooding and various proposals were put forth by governmental regulatory bodies. This interest was spurred by the increasing number of maritime disasters involving large losses of human life, culminating in the loss of the *Titanic* with 1430 lives in 1912. In 1913 an international conference on Safety of Life at Sea considered studies by the British Board of Trade, regulations established by the Society of German Shipowners and a factorial system proposed by the French. The regulations formulated were a compromise among these systems, but owing in part to the advent of World War I, never came into effect. In 1929 another full International Conference on Safety of Life at Sea was convened (Tawresey, 1929). An agreement was finally reached on a factorial system of subdivision employing a *criterion of service* formulation, aimed at evaluating for any given vessel the relative importance of cargo and passenger carrying functions. This system of subdivision, discussed in Section 7, left much to be desired and, except for vague generalities, stability was not considered.

The United States did not immediately ratify the 1929 convention and until 1936 had essentially no mandatory subdivision requirements. Public opinion was aroused by the loss of the *Mohawk* by collision and the *Morro Castle* by fire. The investigations into these losses led to proposed standards of subdivision and stability which substantially improved on the 1929 convention, and these were put into U.S. regulatory form that year. With modifications, these standards are still incorporated in the present U.S. Regulations for Passenger Vessels. Also in 1936 the Maritime Commission was established to revive the American Merchant Marine and to establish an American fleet capable of supporting our military forces in time of war. Since they were considered as naval auxiliaries, all large ships built under subsidy or with the financial support of the Maritime Commission, were, and still are, required to meet not less than a one-compartment standard of subdivision, i.e., they are designed to stay afloat with any one compartment flooded.

Later International Conferences on Safety of Life at Sea (SOLAS) took place in 1948 and 1960, resulting in only minor modifications, adopting higher standards for vessels carrying large number of passengers on short voyages (cross-channel type), and increasing the proportion of ships required to meet a 2-compartment standard. At the 1960 SOLAS Conference, however, new concepts were proposed for future discussion (Richmond, 1960). One stated that the safety of a ship can be measured by the extent of damage it could survive. Another dealt with the survival of damage on a probability basis. While these new concepts were under discussion the capsizing of the liner *Andrea Doria*, which had been built to the 1948 Standards, gave a shocking demonstration of the inadequacies of practical application of the stability provisions of the 1948 convention. This spurred the maritime nations to agree upon a continued study of this subject under the auspices of the then-called Inter-Governmental Maritime Consultative Organization (IMCO),[2] [See 71A] the United Nations affiliate that had been established in 1958.

During the 1960's there were two significant developments. First, the regular meetings of the Technical Subcommittee of IMCO on Subdivision and Stability brought together the technical representatives of the majority of maritime nations in the world. The exchange of information on casualty data and accident experience of all individual countries stimulated the members to strive for more rational and sounder criteria of subdivision. Second, there was a simultaneous expansion throughout the world in the utilization of computers for the calculation of vessel characteristics and subdivision capabilities. From the days in the 1930's and 1940's when the calculation of floodable length curves and damage stability characteristics took weeks of manual calculations, equal or better results could now be obtained by relatively few man-hours of naval architect's labor and a few minutes of modern computer time.

During these years the dramatic rise in concern over the environment, first evidenced in the 1954 Conference on Marine Pollution (MARPOL), coupled with the above mentioned increase in international activities in the subdivision field, resulted in the inclusion of a permissive standard for tanker subdivision in the 1966 U.S. Load Line Act. This was made a required standard in the 1973 MARPOL, and in the U.S. Ports and Waterways Act of 1972.

Meanwhile, proponents of the probabilistic approach to subdivision were discussing and arguing the matter extensively at IMCO. They were successful in getting support for an IMCO Resolution which in 1973 accepted this new approach to subdivision and adopted new standards based on the probabilistic approach, as a permissive alternative to the 1960 SOLAS Conven-

[2] IMCO (Inter-governmental Maritime Consultative Organization) recently has changed its name to IMO (International Maritime Organization).

tion requirements. The 1974 Conference on Safety of Life At Sea, which came into force in 1980, also endorsed this approach as an alternative, but continued to permit the basic factorial provisions of the 1960 Convention. The new alternative regulations are discussed in Robertson, et al (1974), "The New Equivalent International Regulations on Subdivision and Stability of Passenger Ships." See Section 8.

Up to 1970, international agreements on subdivision were limited entirely to passenger ships, which were defined as those carrying more than 12 passengers, and as a permissive rather than a required approach, to tankers. After 1970, however, in rapid succession, the IMCO group put forth international recommendations for the subdivision of bulk chemical carriers and liquefied gas carriers, for the required subdivision of tankers, and for the subdivision of mobile offshore drilling units. Some of these have also been incorporated in U.S. Coast Guard Regulations. Subsequently, a recommendation for subdivision of offshore supply vessels was issued and a recommendation for subdivision of large fishing vessels was contained in the 1977 Convention on the Safety of Fishing Vessels. A recommendation for special purpose craft, including oceanographic ships, training ships, fish processing and research ships, etc. is currently in the process of approval and issuance at IMO, as it is now called, for guidance of designers.

In all of these later conventions and IMO recommendations, the factorial system of subdivision has been dropped completely. The designated ships generally have to meet a one-compartment standard, with some types of ships required to meet a two-compartment standard at certain locations along their lengths. The approach to subdivision has also changed from the previous preoccupation with sinkage and trim to a more realistic treatment, whereby the damaged ship is analyzed for its floodability and stability in both the longitudinal and transverse directions.

With the technical representatives of the maritime nations still meeting regularly at IMO, changes and further development of international regulations and recommendations are inevitable. Naval architects in the future will have to keep in close touch with the regulatory authorities to ensure that their designs meet the regulations in effect at that time.

During the past century, while naval architects were being pushed to develop means of analyzing the effect of flooding on commercial vessels and the means of subdividing these vessels to improve their resistance to sinkage and capsizing after flooding, there was a similar push from naval authorities around the world to improve the ability of naval vessels to survive flooding from the sea due to action by an enemy, as well as by collision. While the causes and extent of the flooding and the required survival conditions are different between commercial and naval vessels, the principles used in analyzing and evaluating the effects of flooding are the same. In the United States, the Navy has been in the forefront of developing means and methods of calculation and analysis to be used in determining the effectiveness of compartmentation in resisting the effects of flooding.

1.3 Need for Standards. Standards are necessary as a basis for regulations if a regulatory body is to administer safety requirements equitably among all commercial vessels under its jurisdiction. National standards are generally established by countries to protect its citizens, its wealth in the form of cargo, and its environment, from the hazards of the sea. It is a truism that the more severe the standard adopted for subdivision and stability, the greater the probability that capital and operating costs will be increased. For example, too close spacing of bulkheads may unnecessarily increase both the first cost and operating costs and may also seriously restrict the vessel's usefulness.

If a nation were to adopt national standards which are in excess of the standards used by competing maritime nations, a competitive advantage would be given to the latter nations. Only by having international standards can these competitive pressures be equalized.

In the early years of international discussions on subdivision and stability, agreements on effective international regulations, particularly for damage stability, were impeded by fear that excessive $\overline{GM}$ and its effect on severity of rolling would seriously curtail the comfort and safety of passengers. This fear has largely been dispelled now as a result of years of satisfactory operating experience with higher $\overline{GM}$, along with the development of both passive and active systems of roll stabilization.

The naval architectural profession welcomes recognized standards which can guide in the many practical compromises between safety and cost which always arise in any new design. They are effective tools for the designers in resisting the demands of nontechnical operators who often cannot grasp the reasons for effective compartmentation. They are, furthermore, very good protection against the possibility of liability for damages in the event of a casualty.

Although the U.S. Navy is also concerned with ship survival in case of collision or grounding, the primary consideration in the subdivision of naval combatant and personnel carrying ships is the probability of surviving an enemy hit or hits, with adequate residual stability and buoyancy. Consequently the Navy requires each type of new ship to be able to survive a specific extent of damage (as a percentage of length), although the standards are classified in some cases.

Before dealing with international standards, the fundamental effects of damage and methods of making calculations of subdivision and damage stability will be discussed.

Section 2
Fundamental Effects of Damage

If the shell of a ship is damaged so as to open one or more internal spaces to the sea, leakage will take place between the sea and these spaces until stable equilibrium is established or until the ship sinks or capsizes. It is impractical to design a ship to withstand any possible damage due to collision, grounding or military action. The degree to which a vessel approaches this ideal is the true measure of its safety.

The probability that a ship will survive damage resulting in flooding is dependent upon a number of variable interrelated factors (Comstock & Robertson, 1961). Some consideration of these factors is useful as a basis for design, as well as in making calculations.

2.1 Extent of Damage and Location and Number of Bulkheads. The length and depth of damage, and its location relative to transverse bulkheads, has a strong influence on probability of survival. In general, it might be expected that the more bulkheads the safer the ship. But damage may occur entirely between adjacent bulkheads or may involve one or more bulkheads. Hence, for a given length of damage, any increase in the number of bulkheads may actually increase the likelihood of bulkhead damage, which would reduce rather than increase the chances of survival. International subdivision standards, discussed in Sections 6-8, specify assumptions to be made regarding extent of damage and indicate how each standard deals with the question of possible damage on a bulkhead.

An international SOLAS working group assembled and analyzed statistical data on collisions, particularly of cargo and passenger ships, to determine location and extent of damage. The results indicated that damages may vary from only 1 or 2m to over 30m (100 ft) in longitudinal extent. Many low-energy collisions occur without producing any penetration below the waterline; i.e., without causing flooding. Very short damages are usually very shallow. Damages of intermediate longitudinal extent, say 6m (20 ft) to 15m (50 ft), may vary in penetration from moderate to deep. Such damages usually result from collisions at an angle of incidence near 90 deg. Under this circumstance, a high-energy collision may result in maximum penetration in association with appreciable longitudinal extent. Very long damages are most infrequent and are likely to be quite shallow.

Navy data on the location and extent of damages due to enemy action are classified, but assumptions made in calculations are discussed in Section 7.

2.2 Effects of Flooding. *(a) Change of draft.* The draft will change so that the displacement of the remaining unflooded part of the ship is equal to the displacement of the ship before damage less the weight of any liquids which were in the space opened to the sea.

(b) Change of trim. The ship will trim until the center of buoyancy of the remaining unflooded part of the ship lies in a transverse plane through the ship's center of gravity and perpendicular to the equilibrium waterline.

(c) Heel. If the flooded space is unsymmetrical with respect to the centerline, the ship will heel until the center of buoyancy of the remaining unflooded part of the ship lies in a fore-and-aft plane through the ship's center of gravity and perpendicular to the equilibrium waterline. If the $\overline{GM}$ in the flooded condition is negative, the flooded ship will be unstable in the upright condition, and even though the flooded space is symmetrical, the ship will either heel until a stable heeled condition is reached or capsize (see Section 3.) Trim and heel may result in further flooding through immersion of openings in bulkheads, side shell or decks (downflooding).

(d) Change of Stability. Flooding changes both the transverse and the longitudinal stability. The initial metacentric height is given by,

$$\overline{GM} = \overline{KB} + \overline{BM} - \overline{KG}.$$

When a ship is flooded, both $\overline{KB}$ and $\overline{BM}$ change. Sinkage results in an increase in $\overline{KB}$. If there is sufficient trim, there may also be an appreciable further increase in $\overline{KB}$ as a result. $\overline{BM}$ tends to decrease because of the loss of the moment of inertia of the flooded part of the waterplane. However, sinkage usually results in an increase in the moment of inertia of the undamaged part of the waterplane, thus tending to compensate for the loss. Also, trim by the stern usually increases the transverse moment of inertia of the undamaged waterplane, and vice versa. For ocean-going ships of usual proportions and arrangements, the combined effect of these factors is usually a net decrease in $\overline{GM}$. However, in ships of low beam-draft ratio or in ships having flare above the waterline up to the bulkhead deck, the net effect may be an increase in $\overline{GM}$. In case of damage to a deep tank, fluid runoff from the tank may reduce $\overline{KG}$.

(e) Change of Freeboard. The increase in draft after flooding results in a decrease in the amount of freeboard. Even though the residual $\overline{GM}$ may be positive, if the freeboard is minimal and the waterline is close to the deck edge, submerging the deck edge at small angles of heel greatly reduces the range of positive righting arm, $\overline{GZ}$, and leaves the vessel vulnerable to the forces of wind and sea. Fig. 1 illustrates this point.

Although, as previously noted, increasing the number of bulkheads increases the likelihood of damage to one or more bulkheads, it also reduces the extent of flooding in cases of damage that do not include these bulkheads. For such cases, it increases the freeboard

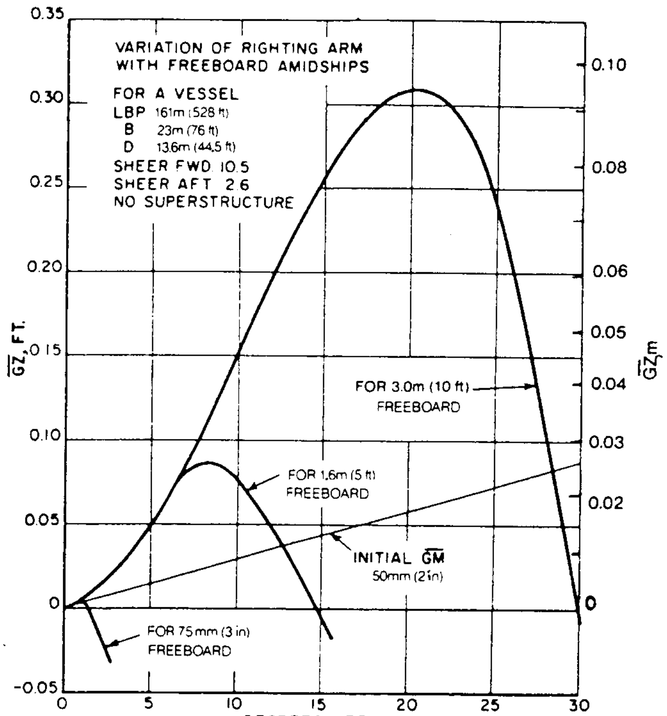


Fig. 1 Variation of righting arm with freeboard amidships

after damage and therefore the likelihood of survival.

For any given number of bulkheads, increasing the freeboard before damage increases the freeboard after damage and improves the chances of survival.

Where portions of the hull and related bulkheads extend watertight above the bulkhead deck, the beneficial effect may be considerable. Even spaces that are not fully tight may contribute to survival if they are tight enough to contribute righting or trimming moment effectively under dynamic conditions of rolling or pitching. For this purpose, tight spaces in the wings of the ship and the ends are most effective. Conversely, reserve buoyancy near the centerline amidships has little effect.

(f) Loss of Ship. Where changes in draft, trim and/or heel necessary to attain stable equilibrium are such as to immerse non-watertight portions of a ship, equilibrium will not be reached because of progressive flooding and the ship will sink either with or without capsizing. Where the loss in $\overline{GM}$ is such that the remaining maximum righting arm is less than any existing heeling arm, capsizing will occur. Even if there were no heeling arm, capsizing could be expected if the $\overline{GM}$ in the damaged condition were negative and if the maximum righting arm were so small as to result in negative dynamical stability. (Section 3.) Practically, even for symmetrical flooding, there is always some heeling arm due to unsymmetrical weights and/or wind.

Where the maximum righting arm in the damaged condition is adequate and where the immersion of non-tight portions of the ship only results in slow extension of flooding, sinking may be quite slow. In such cases, control measures aimed at stopping progressive flooding, either by reducing heel, pumping leakage water or fitting emergency means of checking the flow of water or a combination of such measures may be successful.

In recent deliberations at IMO, looking towards methods of improving the safety of cargo and other vessels where it is impractical to meet any fixed standard of subdivision, the consensus was that providing a master with an instruction manual outlining damage control measures available to minimize flooding would be a valuable contribution to safety.

The U.S. Navy has long recognized this and prepares and issues detailed damage control books and flooding effect diagrams, as do some commercial operators, to aid their crews in damage control. A Flooding Effect Diagram shows by a shading scheme the effect on stability of sea water flooding of various compartments in the ship, including transverse moments for off-center compartments. See Fig. 2.

Some naval ships such as aircraft carriers have layers of side protective tanks of liquid or air to protect the ship's vital ammunition and machinery spaces. In case of damage, flooding of the side protective tanks may produce a large list toward the side of the damage, which requires counterflooding of opposite side tanks to reduce the list. Trim control after damage to aircraft carriers can also be achieved to some extent by flooding tanks at the end opposite to that of the damage.

Rough sea conditions and/or heavy winds substantially increase the reserves necessary to prevent either progressive flooding or capsizing. Fortunately, most collisions occur in harbor approach areas under comparatively favorable sea conditions. An IMO working group has collected data on wind and sea conditions at the time of actual collisions. Damage stability model tests were then carried out in waves. Conclusions were drawn regarding average values of stability necessary for survival as a function of sea state. See Section 8.

2.3 Intact Buoyancy. The general effect of intact buoyancy in a flooded compartment is to decrease both sinkage and trim and therefore to increase the length which may be flooded insofar as sinkage and trim are concerned.

The effect of intact buoyancy on the change in stability with flooding depends upon whether the tops of the intact spaces are above or below the final flooded waterline. If they are above this waterline, the reduction of lost buoyancy, sinkage and rise of $\overline{KB}$, caused by the intact buoyancy, will be accompanied by a reduction in lost waterplane and in lost $\overline{BM}$, and the net effect may be simply that of reducing the effective size of the flooded compartment. If the tops of the W.T. intact spaces are below the final flooded waterline, they still will reduce the rise of $\overline{KB}$, but they will not reduce

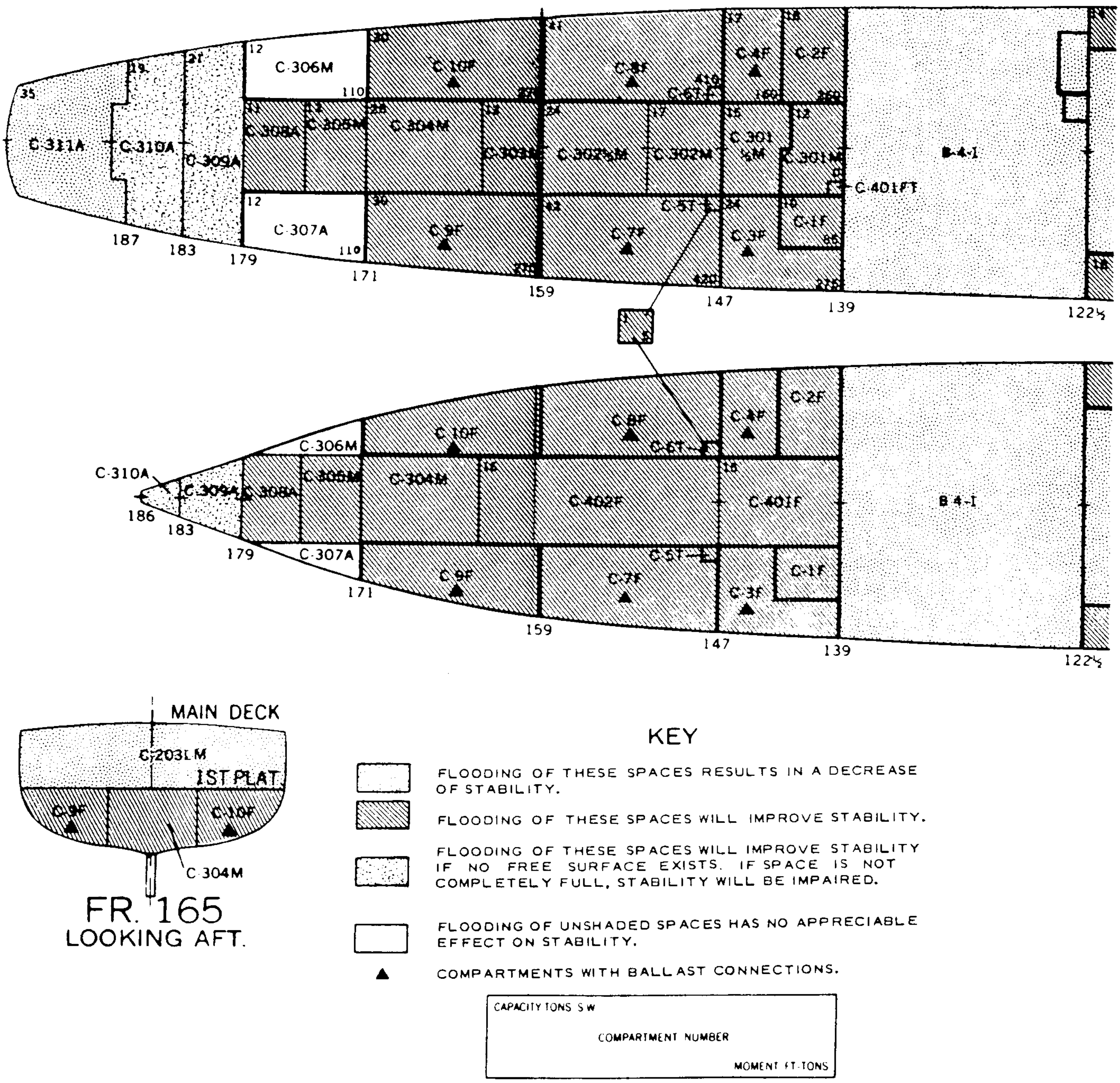


Fig. 2 Portion of Typical Flooding Effect Diagram for Destroyer

the loss of $\overline{BM}$. Hence, submerged intact buoyancy always increases the net loss of $\overline{GM}$. If there is a reserve of stability, but sinkage and trim are critical (as may be the case when end compartments are flooded), intact buoyancy is beneficial. If there is a reserve of freeboard when flooded, but stability-flooded is critical (as is commonly the case when amidships compartments are flooded), submerged intact buoyancy is harmful. If unsymmetrical intact buoyancy extends above the final damaged waterplane its favorable effect on the damaged-condition $\overline{GM}$ may, in some cases, compensate in part for its heeling moment. Thus, the use of high narrow wing tanks extending well above the waterline may be advantageous.

Section 3
Subdivision and Damage Stability Calculations

3.1 General. The *floodable length* at any point in the length of the ship is defined as the maximum portion of the length, having its center at the point in question, that can be symmetrically flooded at the prescribed permeability, without immersing the margin line, which is generally 7.5 cm (3 in.) below the top of the bulkhead deck at the side.

The accurate determination of the floodable length of any portion of a ship requires an analysis of sinkage, trim, and heel to determine that the margin line is not immersed. However, in the following method of calculation, sinkage and trim only are determined. The effects of heel are left to be analyzed by other techniques. When the methods of calculation to determine sinkage and trim were developed in the early part of the century, little thought was given to the effect of heel. The development of techniques to determine heel came later and by common usage the term floodable length has been applied to the curves developed with the understanding that they must be supplemented by damage stability calculations to find the actual allowable length for any compartment.

While the preparation of the curves of floodable length are not essential in regulations using integer compartmentation standards and required residual range and amplitude of righting arm, they are a very valuable tool in the preliminary design stage for any class of ship. They can be very rapidly and thus inexpensively plotted and give the designer a quick visual indication of the probable allowable lengths of compartments. This allows him to select those compartments that may be marginal and perform damage stability and trim checks on them. He can then make any length or weight corrections necessary before calculations are prepared for the rest of the compartments. In ships not required to meet any subdivision standards the curve permits the designer to easily space bulkheads, within the operating constraints imposed by the ship's mission, in such a way that at least certain parts of the ship can be flooded without loss of the ship.

The term *damage stability* is a coined usage having wide acceptance. It is a comprehensive term applying to the calculation of the related changes in draft, trim, heel, and stability as a result of damage to one or more specific compartments of a ship. It also relates to calculation of the intact stability and buoyancy necessary to attain any particular assumed equilibrium damaged condition, as well as to the stability characteristics in that damaged condition.

While the newer standards for damage stability use residual range and amplitude of the righting arm, $\overline{GZ}$, and righting energy represented by the area under the righting arm curves as the basic parameters for compliance with requirements, the use of $\overline{GM}$ is not neglected. The required parameters can be related back to a required $\overline{GM}$ in the intact condition and are invaluable in providing guidance to the operators as to how to load their ships to meet the required safety standards.

3.2 Fundamental Relationships—Floodable Length. A completely rigorous treatment of the sinkage and

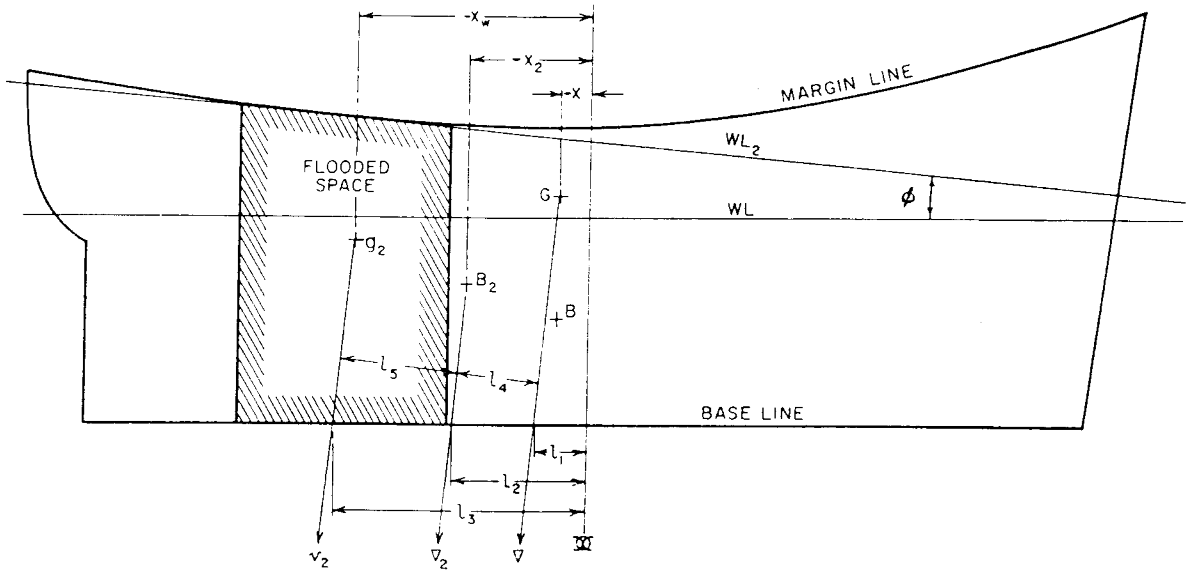


Fig. 3 Diagram for floodable-length calculation

trim from an initial WL to a final waterline WL_2 due to flooding of an unknown part of a vessel's length is illustrated in Fig. 3. In this figure

- ∇ is displacement volume to WL
- B is initial center of buoyancy
- G is initial center of gravity
- v_2 is net volume of flooding water up to WL_2 (i.e., gross vol. $\times\ \mu$)
- g_2 is center of gravity of v_2
- B_2 is center of buoyancy of entire immersed volume up to WL_2
- ∇_2 is entire displacement volume to WL_2
- μ is permeability, the percentage of a space that can be occupied by water.

$\overline{KG}$, $\overline{KB}$, $\overline{Kg}$, and so on are the perpendicular distances of G, B, g, and so on, respectively, from the baseline. For equilibrium,

$$v_2 = \nabla_2 - \nabla;\ v_2 l_5 = \nabla_4;\ \text{therefore } v_2 = \frac{\nabla l_4}{l_5}$$

$$l_1 = x + \overline{KG} \tan \theta$$

where

$$l_2 = x_2 + \overline{KB}_2 \tan \theta$$
$$l_3 = x_w + \overline{KG}_2 \tan \theta$$
$$l_4 = [x_2 - x + \tan \theta\ (\overline{KB}_2 - \overline{KG})] \cos \theta$$
$$l_5 = [x_w = x_2 + \tan \theta\ (\overline{Kg}_2 - \overline{KB}_2)] \cos \theta$$

Therefore,

$$v_2 = \nabla_2 - \nabla = \frac{\nabla[x_2 - x + \tan \theta\ (\overline{KB}_2 - \overline{KG})]}{[x_w - x_2 + \tan \theta(\overline{Kg}_2 - \overline{KB}_2)]}$$

Transposing and rearranging, one gets

$$x_w = \frac{(\nabla_2 x_2 - \nabla x)}{(\nabla_2 - \nabla)} - \tan \theta \left[\overline{Kg}_2 - \frac{(\nabla_2 \overline{KB}_2 - \nabla \overline{KG})}{(\nabla_2 - \nabla)}\right] \quad (1)$$

The tan θ [ ] term involving vertical levers is relatively small. Neglecting it, one may write,

$$v_2 = \nabla_2 - \nabla = \frac{\nabla(x_2 - x)}{(x_w - x_2)} \quad (2)$$

and

$$x_w = \frac{(\nabla_2 x_2 - \nabla x)}{(\nabla_2 - \nabla)} \quad (3)$$

Equations (2) and (3) provide a basis for determining the length and location of flooding that would cause the flooded ship to reach a state of equilibrium at WL_2, neglecting heel. Methods of calculation are discussed in Section 4.

3.3 Fundamental Relationships—Damage Stability. It will be explained in Section 4 that stability and heel, as well as sinkage and trim, after flooding can be evaluated by means of either a *lost buoyancy* or a *trimline added weight* approach. Since the latter has wider applicability and is consistent with the floodable length approach just discussed, its fundamental relationships will be given here. As in the case of floodable length calculations, one assumes an equilibrium damaged condition waterline, calculates the flooding water up to this waterline and subtracts it and its moments from the total displacement and moments up to this waterline, in order to obtain a corresponding before-damage condition. The effect of heel can also be taken into account, all as described in Section 4.

(a) Required $\overline{GM}$ for zero-heel condition. Having determined the draft and trim (if any) before damage, one then can determine the $\overline{GM}$ requirements. Dealing first with the zero-heel condition (either actual symmetrical flooding, or unsymmetrical flooding with assumed equalization of heeling moment), it is convenient to think of the flooding water as tankage having the same vertical moment and free surface. The $\overline{GM}$ in the damaged condition, referred to the gross displacement Δ_2 at T_2, then is expressed by the equation

$$\overline{GM}_{2\Delta_2} = \overline{KM}_2 - \frac{\mu_s i_T}{\Delta_2/\rho} - \overline{KG}_2 \quad (4)$$

where

- Δ_2 is mass displacement $= W_2/g$
- μ_s is surface permeability
- i_T is inertia of flooded waterplane
- $\overline{KM}_2$ is upright metacenter above keel at T_2
- $\dfrac{\mu_s i_T}{\Delta_2/\rho}$ is $\overline{BM}_2$ loss due to free surface of flooding water (if flooded waterplane is unsymmetrical, this is modified to account for TCF of net waterplane)
- $\overline{KG}_2$ is vertical center of gravity of vessel including mass of flooding water, w/g
- ρ is water density

As already noted, the damaged spaces are in open communication with the sea. Therefore, the true displacement in the damaged condition does not include the water in such spaces. It is customary to regard the displacement in the damaged condition as equal to $\Delta_2 - w/g$, (or $W_2 - w$ if weight units are used). In order to provide a minimum positive damaged condition $\overline{GM}$ of 0.05 m (2 in.), based upon $\Delta_2 - w/g$, one then writes,

$$0.05 \times \frac{(\Delta_2 - w/g)}{\Delta_2} = \overline{KM}_2 - \frac{\mu_s i_T}{\Delta_2/\rho} - \overline{KG}_2$$

or

$$\overline{KG}_2 = \overline{KM}_2 - \frac{\mu_s i_T}{\Delta_2/\rho} - 0.05 \times \frac{(\Delta_2 - w/g)}{\Delta_2}$$

The corresponding $\overline{KG}$ before damage (maximum allowable $\overline{KG}$) is then equal to

$$\frac{\overline{KG}_2 \times \Delta_2 - \overline{Kg} \times w/g}{(\Delta_2 - w/g)}$$

where $\overline{Kg}$ is vertical center of gravity of damage water.

Substituting in the preceding equation one obtains

$$\overline{KG} = \frac{\Delta_2 \overline{KM}_2 - \dfrac{\mu_s i_T}{\Delta_2/\rho} - \overline{Kg}\, w/g}{(\Delta_2 - w/g)} - 0.05 \qquad (5)$$

The intact $\overline{GM}$ to meet this condition is therefore $\overline{KM} - \overline{KG}$, where $\overline{KM}$ corresponds to the draft and trim before damage.

(b) Required $\overline{GM}$ to limit heel and righting arms in damaged condition. Referring to Fig. 4, the following definitions and derivation apply:

G is CG of upright ship before damage
G_2 is CG of heeled damaged ship including flooding water

$$t = \frac{(w/g) \times \text{its transverse center of gravity (tcg)}}{\Delta_2}$$

$$\overline{KG}_2 = \frac{\Delta \times \overline{KG} + w/g\, \overline{Kg}}{\Delta_2}$$

where

Δ is displacement before damage $= \Delta_2 - w/g$
$\overline{G_2Z_2}$ is damaged condition righting arm $= [(\overline{KP} - \overline{KG}_2) \tan\phi - t] \cos\phi$
M_2 is metacenter (upright) of intact ship at Δ_2

$$\overline{M_2P} = \frac{\overline{M_2S}}{\sin\phi} = F\,\overline{B_2M_2}$$

$$\overline{KP} - \overline{KG}_2 = \overline{KM}_2 + \frac{\overline{M_2S}}{\sin\phi} - \overline{KG}_2$$

$$\overline{G_2Z_2} = \left[\left(\overline{KM}_2 + \frac{\overline{M_2S}}{\sin\phi} - \frac{\Delta\overline{KG} + \overline{Kg}\, w/g}{\Delta_2}\right) \times \tan\phi - \frac{\overline{Kg}\, w/g}{\Delta_2}\right] \cos\phi$$

$$\overline{G_2Z_2} = \sin\phi \left[\overline{KB}_2 + \overline{B_2M}_2 (F + 1) - \frac{(\Delta_2 - w/g)\,\overline{KG}}{\Delta_2} - \frac{w/g}{\Delta_2}\left(\overline{Kg} + \frac{\text{tcg}}{\tan\phi}\right)\right] \qquad (6)$$

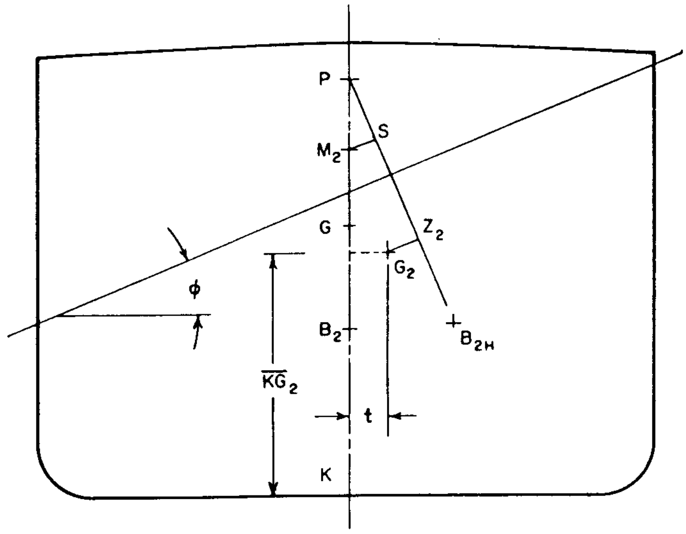


Fig. 4 Diagram for required $\overline{GM}$ to limit heel

Equilibrium exists when $\overline{G_2Z_2} = 0$ and Equation (6) can then be solved for $\overline{KG}$:

$$\overline{KG} = \frac{\Delta_2}{\Delta_2 - w/g}\left[\overline{KB}_2 + \overline{B_2M}_2 (F + 1)\right] - \frac{w/g}{\Delta_2 - w/g}\left(\overline{Kg} + \frac{\text{tcg}}{\tan\phi}\right) \qquad (7)$$

Again, the intact $\overline{GM}$ to meet this condition is $\overline{KM} - \overline{KG}$, and the *required* $\overline{GM}$ is either this value necessary to limit the heel to the maximum allowable value ϕ, or that derived from equation (5), if greater.

When the position of the pole point P is directly determined by integration of the ship's volume to the flooded waterline, as by computer, $\left(\overline{KM}_2 + \dfrac{\overline{M_2S}}{\sin\phi}\right)$ is replaced by $\overline{KP}$. Then

$$\overline{G_2Z_2} = \sin\phi \left[\overline{KP} - \frac{(\Delta_2 - w/g)}{\Delta_2}\overline{KG} - \frac{w/g}{\Delta_2}\left(\overline{KG} + \frac{\text{tcg}}{\tan\phi}\right)\right] \qquad (8)$$

and, for equilibrium:

$$\overline{KG} = \frac{\Delta_2}{\Delta_2 - w/g}\overline{KP} - \frac{w/g}{\Delta_2 - w/g}\left(\overline{KG} + \frac{\text{tcg}}{\tan\phi}\right) \qquad (9)$$

Required $\overline{GM}$, to limit heel is

$$\overline{KM} - \overline{KG}.$$

See sub-section 4.7 for details of derivation and forms for manual calculation.

Although the U.S. Navy sometimes also calculates required $\overline{GM}$, or $\overline{KG}$, the emphasis in design of combatant ships, in particular, is on determining residual righting arms after damage to various compartments or combinations of compartments. (NAVSEC, 1975).

(c) Calculation of Righting Arms in Damaged Condition In the preceding Equation (8) $\overline{G_2Z_2}$ is the net righting arm after flooding, as related to Δ_2, with $\overline{KG}$ corresponding to the $\overline{GM}$ before damage. However, at large angles of heel a more accurate calculation of damaged-condition righting arms is necessary.

In principle, intact-condition righting arms must be modified by the damage. If trim is neglected, this can be accomplished readily by

$$G_2Z_2 = \frac{(\text{Intact vessel rt. mom.}) - (\Delta_2 - w/g)\,\overline{KG}\sin\phi - (\text{Damage heel mom.})}{\Delta_2} \qquad (10)$$

(where both righting moment and heeling moment correspond to the damaged condition draft, T_2, and are referred to an axis intersecting the centerline at the baseline).

If the damage location is such as to result in appreciable change of trim, the change in draft in way of the damage is more than that at the vessel's LCF, and the amount and moment of flooding water are correspondingly affected.

Since heel, even without damage, may result in some trim, a direct calculation of this effect requires in essence the use of heeled-condition Bonjean curves giving both sectional areas and heeling moments. For each damaged-condition draft and heel, the equilibrium trim corresponding to the condition of draft and trim before damage can then be determined by a cross-plotting, or iterative process.

Nowadays, the calculation of residual righting arms after damage, including the effect of trim, is almost always carried out by computer (Section 5.)

Section 4
Manual Subdivision and Damage Stability Calculations

4.1 Manual Floodable Length Calculations—General. Curves of floodable length (and, the corresponding *permissible length* curves described in Section 7) are usually plotted to a vertical scale equal to the longitudinal scale. With such an arrangement, lines drawn from the intersections of the bulkheads with the baseline at an angle $\tan^{-1}$ of 2 will intersect at the midpoint of the compartment and at a height above the baseline that is equal to the length of the compartment. Such curves are sometimes plotted to a vertical scale equal to half the horizontal scale. In such case, the slope of the inclined lines is 1. In either case the intersection of the inclined lines indicates at a glance whether or not the length of a compartment or a combination of compartments is greater than either the permissible length or the floodable length. Fig. 5 illustrates a typical plot of curves of floodable length. Floodable length calculations are based upon the relationships given in 3.2 of Section 3; specifically, equations (1), (2) and (3). The possible errors in permeability assumptions, etc., may be larger than the errors due to neglecting the $\tan\theta$ [ ] term of Equation (1). Accordingly, for manual calculations they are usually neglected and Equations (2) and (3) are used as a basis.

4.2 Direct Method of Calculation. In this method, points on the floodable length curve are calculated for the actual lines of the ship, using Equations (2) and (3) to determine the volume and location of the flooding water that would immerse the ship to the margin line. In general, the procedure is that proposed by Dipl. Ing. F. Shirokauer (1928).

For the solution, no special data, curves or instruments are necessary. The procedure is not unduly long and the accuracy is better than that of comparable methods.

On a profile drawing showing the margin line and a number of transverse stations, Bonjean curves are plotted from a low draft to the margin line. In Fig. 6 the Bonjean curves are shown plotted for ten stations and various scales have been adopted for length, depth, and areas, but any number of stations and any system of scales may be used.

The subdivision load line is drawn on the profile and the trim line parallel to the subdivision load line is drawn tangent to the margin line at its lowest point. To obtain a satisfactory curve of floodable length with the minimum amount of work, the following procedure, as proposed by Shirokauer (1928), is then used. Let,

D be depth from baseline to margin line (at lowest point)
T be draft from baseline to subdivision load line
$H = 1.6D - 1.5T$

At perpendiculars at the extremities of the subdivision length, the distances $H/3$, $2H/3$, and H are laid off as shown in Fig. 6 and tangents are drawn to the margin line from these points. These tangents are designated as in the figure; for example, $3F$ is the tangent drawn from a point on the after perpendicular at a distance of H below the parallel trim line.

The following calculation is then made for each of

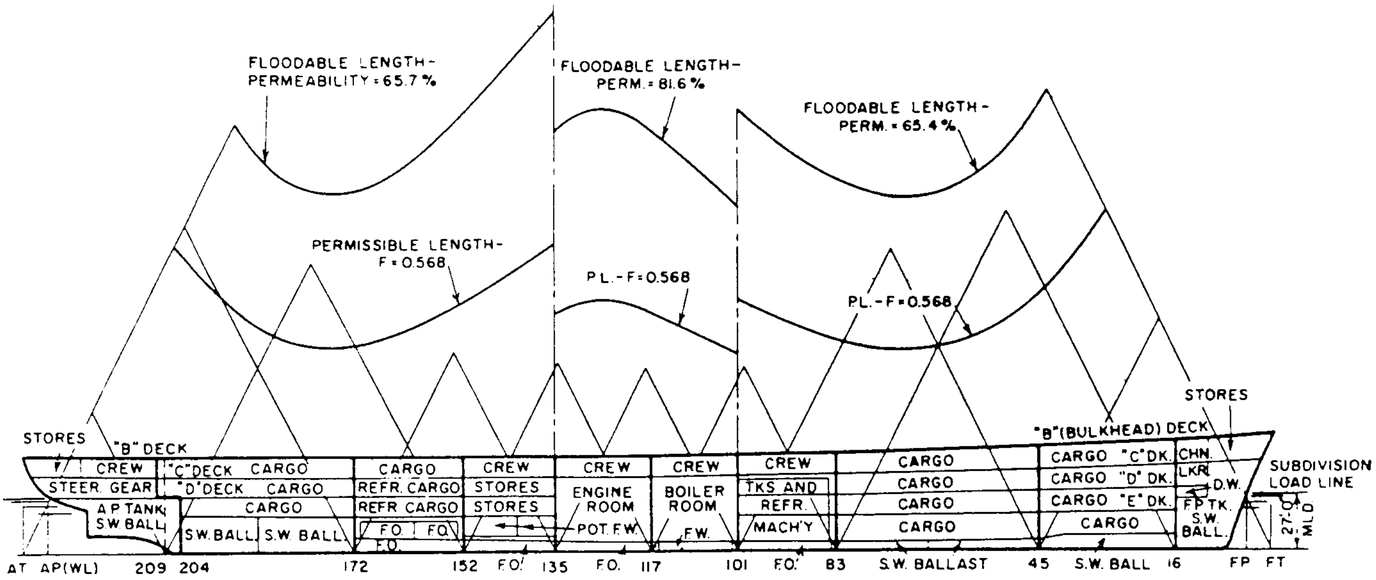


Fig. 5 Floodable-length curves

the three forward trim lines and the subdivision load line. The area of each station up to the trim line is first read from the Bonjean curves. These areas are then integrated by use of Simpson's rule or other rule to obtain the volume of displacement and the distance of LCB from some convenient station such as amidships, Fig. 7. Allowance normally need not be made for appendages. Neglecting them, in fact, tends to compensate for disregarding the effect of the vertical levers in Eq. (1).

The next step is to calculate for each trim line the corresponding volume of damage water v_2 and the longitudinal distance x_w between its center of gravity and amidships. The volume of damage water v_2 is the volume of displacement below the trim line less the volume of displacement of the undamaged ship at the subdivision load line. The distance x_w is calculated from equation (3). Fig. 7 has suitable spaces for the tabulation of the values of v_2 and x_w for each trim line.

It should be noted that, if either B_2 or G lies on a different side of amidships than that shown in Fig. 3, the signs must be changed accordingly.

After v_2 and x_w have been determined for each of the trim lines, the interpolation curves should be drawn as shown in Fig. 8. The parallel lines labelled 3A, 2A, and so on, correspond to the trim lines and are spaced any equal distance apart.

Ordinates on the curves are plotted vertically from the horizontal axis shown. Since the curves of LCG of damage water have considerable curvature in the vicinity of the 3F and 3A trim lines, additional points are necessary to determine their shape. The other curves have very little curvature in this vicinity, and points from them may be used with sufficient accuracy to determine additional points on the LCG curves.

For example, in Fig. 8, another vertical line may be drawn halfway between the 2F and 3F lines. This will correspond to a 2½F trim line. Let v_2' be the value of

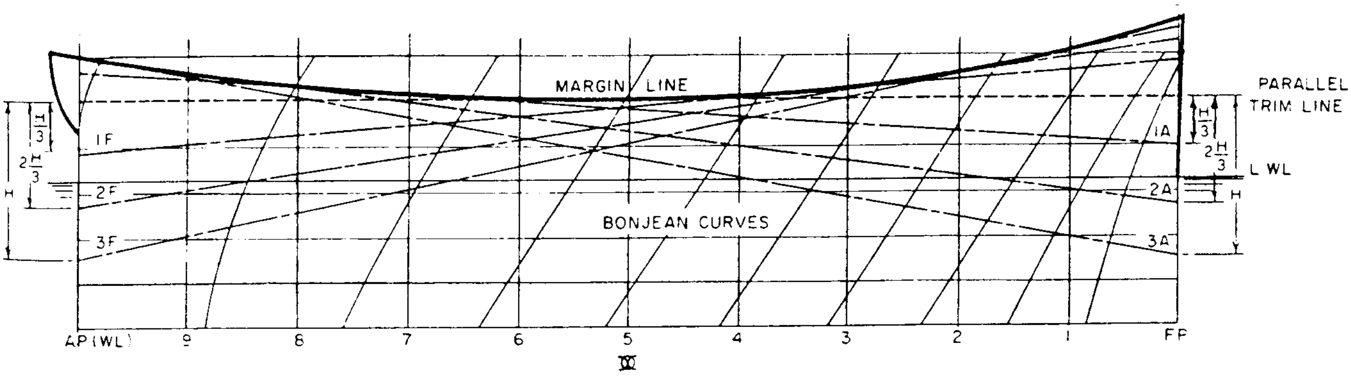


Fig. 6 Bonjean curves and trimlines for floodable-length calculations

S = SPACING OF STATIONS S = $\frac{S}{3}$ =	TRIMMED DISPLACEMENTS AND CENTERS	SHEET SHIP DATE BY:

STATION	SM VOL.	SM MT.	SECTION AREAS TO TRIM LINES: SUBDIVIS. LOAD LINE	3A	2A	1A	PAR.	1F	2F	3F
0	$\frac{1}{2}$	$2\frac{1}{2}$								
$\frac{1}{2}$	2	9								
1	$1\frac{1}{2}$	6								
2	4	12								
3	2	4								
4	4	4								
5	2	0								
6	4	4								
7	2	4								
8	4	12								
9	$1\frac{1}{2}$	6								
$9\frac{1}{2}$	2	9								
10	$\frac{1}{2}$	$2\frac{1}{2}$								
Σ SM VOL. x A = $\Sigma f(\nabla)$										
Σ SM MT. x A = $\Sigma f(M)$										
① DISPLACEMENT $\Sigma f(\nabla) \times \frac{S}{3}$			∇	∇_2	∇_2	∇_2	∇_2	∇_2	∇_2	∇_2
② DW. VOLUME $= \nabla_2 - \nabla$			X	v_2	v_2	v_2	v_2	v_2	v_2	v_2
③ L.C.B.= $\frac{\Sigma f(M)}{\Sigma f(\nabla)} \times S$			x	x_2	x_2	x_2	x_2	x_2	x_2	x_2
④ SHIFT OF L.C.B $= x_2 - x$			X							
⑤ C.G.DW. FROM L.C.B. $\frac{\text{LOAD DISPLT}}{\text{DW. VOLUME}} \times$ ④			X							
⑥ C.G. DW. FROM Ⅲ ③ + ⑤			X	x_w	x_w	x_w	x_w	x_w	x_w	x_w

∇, THE VOLUME OF DISPLACEMENT AT SUBDIVISION LOAD LINE

∇_2, THE VOLUME OF DISPLACEMENT AT STATED CONDITION OF DAMAGE

x, LCB OF SHIP ON SUBDIVISION LOAD LINE, MEASURED FROM Ⅲ

x_2, LCB OF SHIP AT STATED CONDITION OF DAMAGE MEASURED FROM Ⅲ

Fig. 7 Floodable-length calculation form, m or ft

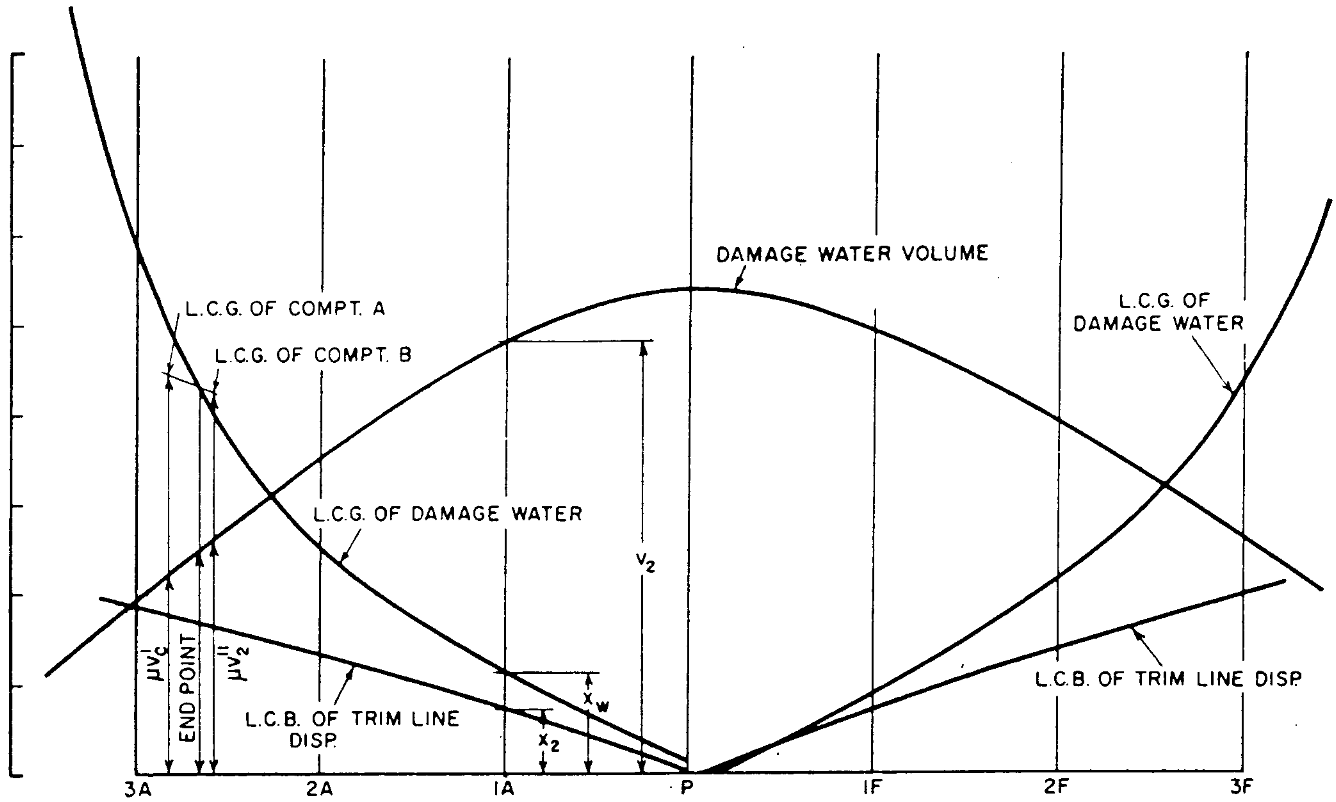


Fig. 8 Interpolation curves

the ordinate of the damage water volume curve and x_2' be the value of the ordinate of the LCB curve. Then, since V, the volume of intact displacement, and x, the LCB of the intact displacement, are known, the value of x_w' will be

$$x_w' = \frac{\nabla}{v_2'}(x_2' - x) + x_2' \qquad (11)$$

The interpolation curves, if they are found to plot fairly, serve as a check on the previous calculations. Their primary purpose, however, is to facilitate calculation of the end points and auxiliary points of the floodable-length curve (following).

Sectional areas read from the Bonjean curves in Fig. 7 are now plotted as a sectional area curve of each trim line as shown in Fig. 9. These sectional area curves are used in conjunction with the interpolation curves, Fig. 8, to determine points on the floodable length curve.

For example, let us take the floodable length calculations for trim line 2A. Let

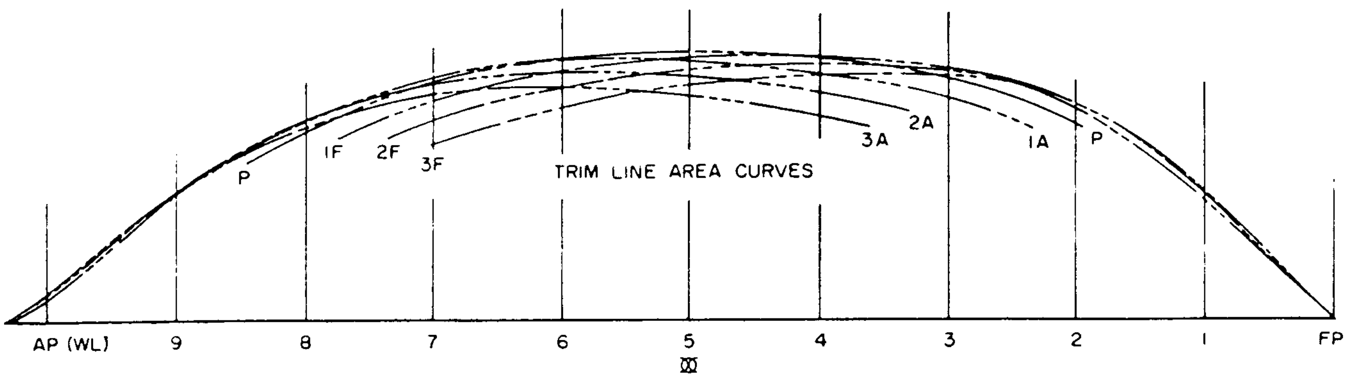


Fig. 9 Section area curves for trim lines

v_2 be net volume of flooding water (from Fig. 8)
x_w be distance of its center of gravity from amidships (from Fig. 8)
θ be assumed permeability in percent
v_c is volume of compartment $= \frac{v_2}{\mu} \times 100$
x_m be distance of midlength of compartment from center of gravity of damage water (or compartment)
x_c be distance of midlength of compartment from amidships
l be length of compartment or floodable length at assumed permeability.

The method is one of trial and error; so the first step is to guess as to the distance x_m of the midlength from the center of gravity of damage water and as to the length of compartment which will give a volume $v_c = (v_2/\mu) \times 100$. The length may be estimated by dividing the required volume v_c by an assumed mean section area. This length is laid off from the assumed position of the middle of the compartment, as shown in Fig. 10, and gives *abcd* as a compartment. By Simpson's rule, Fig. 11, with five ordinates, the volume of this compartment and the distance of its center of gravity from its midlength may be computed. This computed volume should equal the required volume v_c, and the distance of its center of gravity from the midlength should equal the assumed distance x_m. Usually a second try is necessary, such as one which gives the compartment *a'b'c'd'* of Fig. 10, for example. The correct length of the compartment and the corresponding value of x_c are obtained by interpolation in Fig. 8 and are plotted as a point on the floodable length curve (Fig. 5).

A point on the floodable length curve is calculated for each of the trim lines. On some ships a compartment for the 3A or 3F trim line cannot be found. Such a development indicates that the limiting trim line for the end point of the floodable length curve lies between 2A and 3A or 2F and 3F. An additional point, such as is given by a 2½F or 2½A trim line, is then desirable. The volume and LCG of damage water for such a trim line is taken directly from the interpolation curves, Fig. 8, and the corresponding point on the floodable length curve is determined in the same way as for any other point. Similarly, data for other additional points required to get a fair floodable length curve may be taken from the interpolation curves.

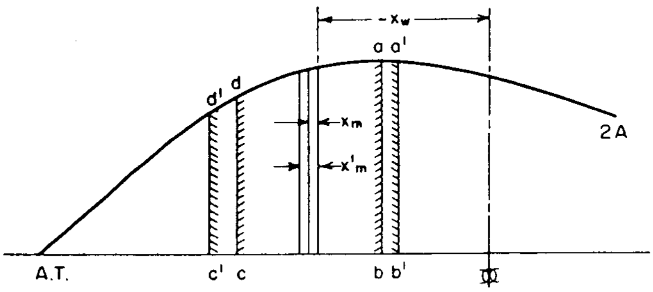


Fig. 10 Volume and C. G. of assumed compartment

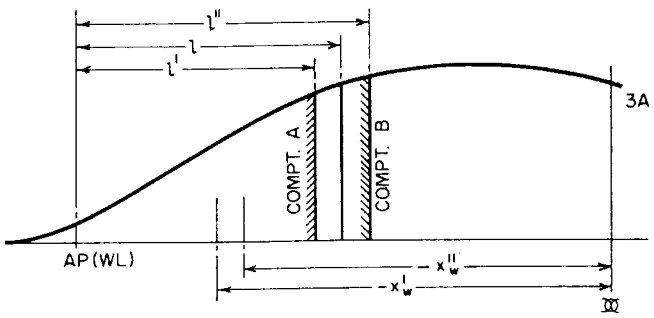


Fig. 12 Diagram for calculating endpoint

In using the interpolation curves to determine the end points of the floodable length curve, a somewhat different procedure is used. The exact trim lines which correspond to the end points are not known but obviously they will be close to trim lines 3A and 3F, respectively. Hence, the sectional area curves of these trim lines are used in the end-point calculations. From the trend of the floodable length curve as plotted from the points already determined, reasonably close estimates can be made of the lengths of the ordinates at the ends of the curve. These ordinates are the respective floodable lengths at the extreme ends of the ship. To obtain more accurate values of the ordinates, each end of the ship is treated separately by the following method.

At the after end of the ship, for example, two compartments are laid down on curve 3A of Fig. 9 to form a diagram similar to Fig. 12. One of these compartments A is slightly shorter than the estimated floodable length, while the other compartment B is slightly longer than this estimated length. By Simpson's rule and with sectional areas from the 3A trim line of Fig. 9, calculations are made as indicated in Fig. 13 to get

v_c' = volume of compartment A
v_c'' = volume of compartment B
x_w' = distance from amidships of center of gravity of compartment A
x_w'' = distance from amidships of center of gravity of compartment B
$\mu v_c'$ = damage water volume in compartment A
$\mu v_c''$ = damage water volume in compartment B

In Fig. 8 an ordinate is erected which cuts the curve of damage water volume at height $\mu v_c'$ and upon this ordinate is plotted the LCG of compartment A at the distance x_w above the axis. Similarly an ordinate for compartment B is erected and the LCG of this compartment is plotted on it. Between these two LCG points a straight line is drawn which cuts the curve

TRIM LINE No.______	**FLOODABLE LENGTH CALCULATION**	SHEET SHIP DATE BY:

L.C.G. OF DAMAGE WATER FROM ⊠ = X_w = ______
DAMAGE WATER VOLUME = v_2 = ______
COMPARTMENT VOLUME AT____% PERMEABILITY = v_c = ______

A

(1) TRIAL FLOODABLE LENGTH = $\frac{v_c}{\text{SEC. AREA (MEAN}}$ = ℓ = ____

(2) TRIAL x_m ____ ; CORRESPONDING x_c ____

SECTION NUMBER	SECTION AREA	SM VOL.	SM MT.
AFT 0		1	+2
1		4	+4
2		2	0
3		4	-4
FOR'D 4		1	-2
$\Sigma f(V)$			
$\Sigma f(M)$			

(3) S (STA. SPACING) = $\frac{\ell}{4}$ = ____ ; $\frac{S}{3}$ = ____

(4) COMPT. VOL. = $\Sigma f(V) \times \frac{S}{3}$ = ____

(5) COMPUTED $x_m = \frac{\Sigma f(M)}{\Sigma f(V)} \times S$ = ____

(6) APPROX. FLOOD. LENGTH = $\ell \times \frac{v_c}{(4)}$ = ____

(7) APPROX. $x_c = x_w + x_m$ = ____

B

2nd TRIAL FLOODABLE LENGTH, (6) = ____

2nd TRIAL x_c, (7) = ____

SECTION NUMBER	SECTION AREA	SM VOL.	SM MT.
AFT 0		1	+ 2
1		4	+4
2		2	0
3		4	-4
FOR'D. 4		1	-2
$\Sigma f(V)$			
$\Sigma f(M)$			

(8) S = ____ ; $\frac{S}{3}$ = ____

(9) COMPT. VOL. = $\Sigma f(V) \times \frac{S}{3}$ = ____

(10) $x'_m = \frac{\Sigma f(M)}{\Sigma f(V)} \times S$ = ____

(11) FLOODABLE LENGTH = (6) $\times \frac{v_c}{(9)}$ = ____

(12) $x_c = x_w +$ (10) = ____

Fig. 11 Calculation form for a point on the floodable-length curve, m or ft.
(Calculations *A* and *B* apply to two trial compartments for each of which *l* and x_m are estimated. Additional trials may be necessary.)

L = LENGTH OF VESSEL	**END POINT CALCULATION**	SHEET
		SHIP
		DATE
		BY:

ASSUMED COMPARTMENT "A"

SECTION	SM VOL.	SM MT.	SECTION AREA
0	1	0	
1	4	4	
2	2	4	
3	4	12	
4	1	4	
$\Sigma f(V)$			
$\Sigma f(M)$			

ASSUMED FLOODABLE LENGTH = ______ $= l'$

S (SPACING OF SECTIONS) $= \frac{l'}{4} =$ ______ ; $\frac{S}{3} =$ ______

$v_c' = \Sigma f(V) \times \frac{S}{3} =$ ______

Dw VOLUME $= \mu v_c' =$ ______

C.G. Dw FROM SEC. 0 $= C = \frac{\Sigma f(M)}{\Sigma f(V)} \times S =$ ______

C.G. Dw FROM ⊗ $= \frac{L}{2} - C =$ ______ $= X_w'$

ASSUMED COMPARTMENT "B"

SECTION	SM VOL.	SM MT.	SECTION AREA
0	1	0	
1	4	4	
2	2	4	
3	4	12	
4	1	4	
$\Sigma f(V)$			
$\Sigma f(M)$			

ASSUMED FLOODABLE LENGTH = ______ $= l''$

S = ______ $\frac{S}{3} =$ ______

$v_c'' = \Sigma f(V) \times \frac{S}{3} =$ ______

D_w VOLUME $= \mu v_c'' =$ ______

C.G. Dw FROM SEC. 0 $= C = \frac{\Sigma f(M)}{\Sigma f(V)} \times S =$ ______

C.G. Dw FROM ⊗ $= \frac{L}{2} - C =$ ______ $= X_w''$

Dw VOLUME FOR FLOODABLE END COMPARTMENT = ______

MOLDED VOLUME OF FLOODABLE END COMPARTMENT $= v_c =$ ______

$l = l' + \frac{v_c - v_c'}{v_c'' - v_c'}(l'' - l') = +$ ___X___

FLOODABLE LENGTH = ______

Fig. 13 Form for calculating endpoint (m or ft)

of LCG of damage water at the ordinate corresponding to the desired trim line for the end point of the floodable length curve. At this ordinate the volume of damage water is read from Fig. 8; this volume divided by the permeability gives the volume of the end compartment. The length of the end compartment found by Equation

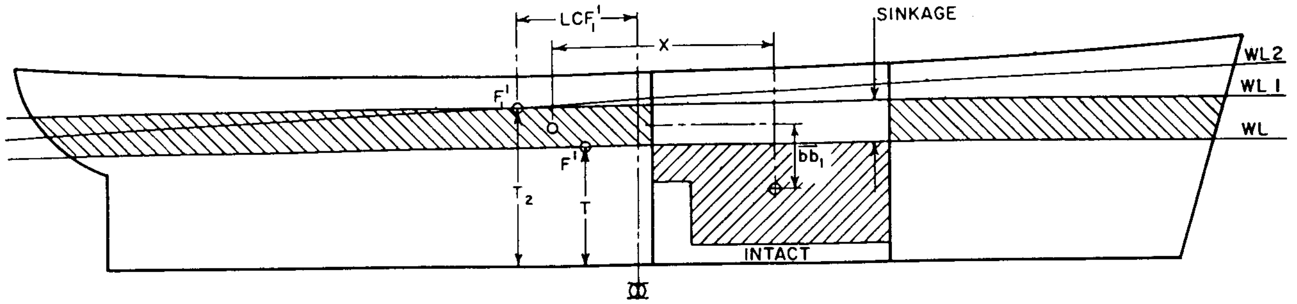


Fig. 14 Sinkage and trim by lost buoyancy method

(12) determines the end point of the floodable length curve. Let

v_c be volume of end compartment
l' be length of compartment A
l'' be length of compartment B
l be length of end compartment

Then

$$l = l' + \frac{(v_c - v_c')}{v_c'' - v_c'}(l'' - l') \qquad (12)$$

The other end point is found in a similar manner. See also Muckle (1963).

When the portions of the hull below the margin line but forward of the FP and abaft the AP are not included in calculating the displacement volumes and the flooding water volumes (see Figs. 7, 11, 12 and 13) the calculated value of the forward-end floodable length is measured aft from the FP and that of the after-end floodable length is measured forward from the AP. However, in constructing the floodable length curves, Fig. 5, the forward terminus of the diagram (FT) should be taken at the forward extremity of the margin line, and the corresponding terminal floodable length is equal to the calculated forward-end floodable length plus the longitudinal distance between the FP and the FT. Similarly, the after terminus of the diagram (AT) should be taken at the after extremity of the margin line and the corresponding terminal floodable length is equal to the calculated after floodable length plus the longitudinal distance between the AP and the AT.

4.3 Manual Damage Stability Calculations—General. The methods of calculation shown in this section were developed early in this century for use on naval ships and commercial passenger vessels, and during the time when manual calculation was the only method available. While the basic principles are the same, modern computer programs, particularly the widely used Ship Hull Characteristics Program (SHCP) (NAVSEA, 1976), use entirely different techniques to determine damage stability. These are described in Section 5. The manual calculations described in this section are applicable only to vessels where the survival criteria (Section 7) specify minimum $\overline{GM}$, maximum heel, and minimum freeboard.

When stability criteria for naval or other ships specify required residual range and amplitude of righting arms, then complete computer calculations of cross curves and/or righting arms after damage are required, as discussed in Section 5.

4.4 Equilibrium Draft, Trim, and Heel After Flooding. The draft, trim and heel in flooded condition after equilibrium has been established can be calculated by starting with an assumed service condition, calculating the lost buoyancy due to a compartment or compartments being opened to the sea, and equating that lost buoyancy and its moments to the buoyancy gain and moments accompanying sinkage, trim, and heel of the remaining intact part of the ship.

This procedure is convenient and simple to use if the form of the vessel and the configuration of the flooded space are such that the resulting sinkage, trim, and heel do not involve extreme or discontinuous changes in the remaining undamaged part of the waterline plane. Consequently, this procedure, commonly known as the *lost-buoyancy* method, is often used for merchant ships.

Alternatively, one may assume an equilibrium damaged condition waterline, calculate the flooding water up to this waterline, and subtract it and its moments from the total displacement and moments up to this waterline in order to obtain a corresponding before-damage condition.

This second procedure is commonly known as the *trim-line added-weight* method. This is a misnomer, since water in spaces open to the sea and free to run in or out does not actually add to a vessel's weight. For calculation purposes it is convenient to regard such flooding water as adding to the displacement; however, it must be remembered that the resulting (virtual) displacement not only differs from the initial displacement but varies with change in trim or heel.

Since the trim-line added-weight method involves a direct integration of volumes up to the damaged condition waterplane, it is just as well adapted to dealing with complex flooding conditions as with simple ones. It does require, however, the determination by iteration of drafts and trims after flooding that correspond to undamaged values covering the range of actual service conditions. As will be shown, this may be accomplished in a systematic manner without great difficulty. It should be noted that the fundamental relationships used in direct floodable length calculations and illustrated by Fig. 3, Section 3, and the accompanying text follow the trim-line added-weight method.

Complete procedures for both methods are described here. In practice some calculators may depart from these procedures for convenience or simplification, or personal preference. However, the principles still apply.

In both methods it is usually assumed that trim and heel are independent functions. This is not exact, but is adequate for ordinary merchant vessels. For vessels with asymmetric waterplanes, such as those having fine bows and transom sterns, the trim-line added-weight method is preferable and can be modified to take account of trim and heel interaction.

4.5 Displacement and $\overline{GM}$ in Flooded Condition. As already noted, liquids in damaged spaces in open communication with the sea obviously do not act as a part of a vessel's weight, i.e., a vessel's displacement in the damaged condition is equal to its initial undamaged displacement less the weight of any liquids which were in breached tanks before damage. This assumption is used when calculations are made by the lost buoyancy method, in which flooding water is considered as lost buoyancy rather than added weight.

It should be noted that when calculations are made by the added weight method, not only is the virtual displacement different from the initial displacement, but the $\overline{GM}$ has a different meaning—since both $\overline{KG}$ and $\overline{KM}$ are different. However, the product of displacement and $\overline{GM}$ should remain unchanged. Hence, if a stability criterion specifies a minimum residual $\overline{GM}$ of 5 cm (2 in.), the lost buoyancy approach is intended, and the corresponding $\overline{GM}$ by added weight is 5 cm x Δ/Δ_v, where Δ is the initial displacement and Δ_v is the virtual displacement after damage.

4.6 Lost-Buoyancy Method. For convenience, the given procedures make maximum use of the quantities ordinarily shown on the curves of form and are sufficiently accurate for ordinary cases. Figs. 15 and 16 illustrate tabular forms for making the following lost-buoyancy-method calculations. For greater accuracy, or where complicated flooding configurations are involved, trim-line added-weight calculations are recommended.

(a) Determination of sinkage and trim: The ship in Fig. 14, initially at waterline WL, comes to float at waterline WL_2 because of the sinkage and trim due to flooding of one or more of its compartments.

We may imagine that, when flooding takes place, the ship is restrained temporarily from trimming. The net lost buoyancy below WL, i.e., the net volume v' of damage water below that waterline, must be replaced by an equal gain in buoyancy above WL. Hence, the sinkage or change in mean draft is approximately:

$$\text{Sinkage} = \frac{v'}{A'} = \frac{(v - \text{intact buoyancy})\,\mu - P/\rho}{A - \mu_s a} \tag{12}$$

where

v is molded volume of flooded compartment below WL
v' is net lost buoyancy below WL
μ is permeability of compartment
P is total mass of liquids, if any, in breached tanks before damage[3]
ρ is density of liquid in breached tanks t/m^3
μ_s is surface permeability of compartment
A is area of waterplane WL
a is area of portion of waterplane WL within compartment
A' is net area of waterplane WL remaining intact after flooding $= A - \mu_s a$

After the sinkage has been estimated by Equation (12) a second and closer approximation may be made by

$$\text{Sinkage} = \frac{2v'}{A' + A_1'} \tag{13}$$

where

A_1' is remaining area of impaired waterplane $WL_1 = A_1 - \mu_s a_1$
a_1 is area of portion of impaired waterplane WL_1 within compartment

If A' and A_1' are each replaced by the remaining TPcm at WL and WL_1,

$$\text{Sinkage (m)} = \frac{v'\rho}{50 \times \text{sum of remaining TPcm values}} \tag{14}$$

Or in English units (ft and long tons),

$$\text{Sinkage (ft) in SW} = \frac{v'/35}{6 \times \text{sum of remaining TPI values}} \tag{14a}$$

When the imaginary restraint against trimming is removed, the ship comes under the action of a trimming moment which is equal to

$$\text{Trimming moment} = v'\,\rho\,x \tag{15}$$

[3] When, in accordance with Section 7.6, tanks are taken at zero permeability, $P = 0$.

DAMAGE STABILITY - LOST BUOYANCY METHOD - SINKAGE AND TRIM - BASIC DATA

SHIP ______________________ DATE ______________ PAGE 1

DAMAGE EXTENT ______________________ BY ______________

ITEM No.	SOURCE	DESCRIPTION						
(1)	----------	T, DRAFT BEFORE DAMAGE						
(2)	CURVES OF FORM	DISPLACEMENT Δ						
(3)	CURVES OF FORM	TONNES PER m						
(4)	CURVES OF FORM	LCF F+ A−						
(5)	CURVES OF FORM	$\overline{KM}$						
(6)	CURVES OF FORM	$\overline{KB}$						
(7)	COMPARTMENT CALCULATIONS	NET LOST BUOYANCY, $\frac{w}{g}$ ✩						
(8)	COMPARTMENT CALCULATIONS	VERTICAL CENTER OF (7)						
(9)	COMPARTMENT CALCULATIONS	CENTER OF (7) FROM MIDSHIPS F+ A−						
(10)	COMPARTMENT CALCULATIONS	CENTER OF (7) FROM CL P− S+						
(11)	COMPARTMENT CALCULATIONS	LOST TONNES PER m						
(12)	COMPARTMENT CALCULATIONS	CENTER OF (11) FROM MIDSHIPS F+ A−						
(13)	COMPARTMENT CALCULATIONS	CENTER OF (11) FROM CL P− S+						
(14)	(3) - (11)	REMAINING TONNES PER m						
(15)	$\frac{(3) \times (4) - (11) \times (12)}{(14)}$	CENTER OF (14) FROM MIDSHIPS F+ A−						
(16)	$\frac{(7)}{(14)}$	APPROXIMATE SINKAGE						
(17)	(1) + (16)	APPROXIMATE DRAFT AFTER FLOODING						
(18)	CURVES OF FORM	TONNES PER m AT (17)						
(19)	COMPARTMENT CALCULATIONS	LOST TONNES PER m AT (17)						
(20)	(18) - (19)	REMAINING TONNES PER m						
(21)	$\frac{2 \times (7)}{(14) + (20)}$	SINKAGE						
(22)	(1) + (21)	DRAFT AFTER FLOODING						
(23)	CURVES OF FORM	TONNES PER m AT (22)						
(24)	CURVES OF FORM	LCF AT (22) F+ A−						
(25)	CURVES OF FORM	MOM. TO TRIM ONE m AT (22)						
(26)	COMPARTMENT CALCULATIONS	LOST TONNES PER m AT (22)						
(27)	COMPARTMENT CALCULATIONS	CENTER OF (26) FROM MIDSHIPS F+ A−						
(28)	COMPARTMENT CALCULATIONS	CENTER OF (26) FROM CL P− S+						
(29)	$\frac{(23) \times (24) - (26) \times (27)}{(23) - (26)}$	CENTER OF REMAINING TPm F+ A−						
(30)	$(9) - \frac{[(15) + (29)]}{2}$	TRIMMING LEVER F+ A−						
(31)	(7) × (30)	TRIMMING MOMENT F+ A−						
(32)	$\frac{(23) \times (26) \times [(24) - (27)]^2}{L \times [(23) - (26)]}$	----------						
(33)	----------	AVERAGE LENGTH OF LOST WATERPLANE, S						
(34)	$\frac{(26) \times (33)^2}{12L}$	----------						
(35)	(25) - (32) - (34)	NET MOMENT TO TRIM ONE m						
(36)	(31) / (35)	TRIM IN m F+ A−						

✩ NOTE: ITEM 7, MASS OF NET BUOYANCY = $\Sigma \mu \rho v$ (at T) FOR ALL SPACES OPENED TO SEA LESS TOTAL TONS OF LIQUIDS WHICH WERE IN ANY BREACHED TANKS BEFORE DAMAGE

Fig. 15 Form for calculation of sinkage and trim, lost buoyancy method where x is the distance from the center of volume of the net lost buoyancy under WL to the center of volume of the buoyancy gained above WL. The latter point lies about midway between the respective centers of flotation (F' and F_1') of the remaining areas of the impaired waterplanes WL and WL_1. The moment to trim 1 cm may then be taken as (from Eq. (6), Chapter II),

$$\text{MTcm}'_1 = \frac{\rho I_{L_1}'}{100\ L} \tag{16}$$

where MTcm'_1, is the moment to change trim 1 cm for the damaged ship and I_{L_1}' is the longitudinal moment of inertia of the intact portion of waterplane WL_1 about a transverse axis through its center of area, F_1'. Then

$$I'_{L_1} = I_{L_1} + A_1\,(\overline{\otimes F_1})^2 - (A_1 - \mu_s a_1)\,(\overline{\otimes F_1'})^2 - \mu_s\,[a_1\,(\overline{\otimes f_1})^2 + i_{L_1}] \tag{17}$$

where

I_{L_1} *is* longitudinal moment of inertia of undamaged waterplane WL_1 about its center of flotation, F_1

$\overline{\otimes f_1}$ is center of a_1 from amidships

i_{L_1} *is* longitudinal moment of inertia of area, a_1 about its center

In general,

$$I_L = 100/\rho \times \text{moment to trim 1 cm, MTcm}$$
$$A = 100/\rho \times \text{tons per cm, TPcm}$$
$$\mu_s a_1 = 100/\rho \times \text{lost tons per cm, tpcm,}$$
$$\mu_s i_L = \frac{\mu_s a_1 S^2}{12} = \frac{100}{12\rho} \times \text{tpcm}_1 \times S^2$$

where S = mean length of lost area and

$$\overline{\otimes F_1'} = \frac{\text{TPcm}_1 \times \overline{\otimes F_1} - \text{tpcm}_1 \times \overline{\otimes f_1}}{\text{TPcm}_1 - \text{tpcm}_1}$$

Therefore, Equations (16) and (17) can be combined to produce:

Net moment to trim 1 m at d_2

$$= 100\left\{\text{MTcm}_1 - \frac{\text{TPcm}_1 \times \text{tpcm}_1 \times [\overline{\otimes F_1} - \overline{\otimes f_1}]^2}{L \times [\text{TPcm}_1 - \text{tpcm}_1]} - \frac{\text{tpcm}_1 \times S^2}{12L}\right\} \tag{18}$$

In English units (ft and long tons), net moment to trim 1 ft at d_2

$$= 12\left\{\text{MTI}_1 - \frac{\text{TPI}_1 \times \text{tpi}_1 \times [\overline{\otimes F_1} - \overline{\otimes f_1}]^2}{L \times [\text{TPI}_1 - \text{tpi}_1]} - \frac{\text{tpi}_1 \times S^2}{12L}\right\} \tag{18a}$$

The calculations may be carried out conveniently in the following steps:

1. Calculate the net lost buoyancy v' below WL, and the longitudinal center of this volume.
2. Determine the sinkage from Equation (12) and later from Equation (13).
3. Calculate the location of F_1', the center of flotation of the remaining area of the impaired waterplane WL_1.
4. From Equation (18) calculate the moment to change trim 1 cm.
5. Calculate the change of trim from Equations (15) and (18).
6. If the change of trim is by the bow (positive) the approximate draft at the bow of the flooded ship is the original draft plus sinkage plus the product of change in trim and $[0.5 - (\overline{\otimes F_1'}/L)]$, and the draft at the stern is the original draft plus sinkage minus the product of change in trim and $[0.5 + (\overline{\otimes F_1'}/L)]$. These drafts determine the trimmed waterline WL_2.

(*b*) *Change of* $\overline{GM}$. The change of $\overline{GM}$ (gain or loss) due to flooding conveniently may be considered as made up of three parts; i.e., a decrease due to lost waterplane, an increase due to sinkage, and an increase due to trim.

1. The decrease in $\overline{BM}$ due to loss of waterplane moment of inertia is

$$\overline{BM} - \frac{I_{T2} - \mu_s i_{T2}}{\Delta/\rho} \tag{19}$$

where

$\overline{BM}$ is $\overline{BM}$ at initial undamaged condition

Δ is corresponding displacement

I_{T2} is transverse moment of inertia of undamaged WL_2

$\mu_s i_{T2}$ is net lost transverse moment of inertia

The foregoing moments of inertia are taken about the transverse center of gravity of the remaining intact waterplane at WL_2. It is somewhat more convenient, however, to take the moments of inertia about the centerline. If

I_{T2CL} is transverse moment of inertia of undamaged WL_2 about centerline

$\mu_s i_{T2CL}$ is net lost transverse moment of inertia about CL

A_2 is waterplane area at WL_2

$\mu_s a_2$ is net lost water plane area, and

t_2 is its center from centerline

the transverse center of gravity of the remaining waterplane is

DAMAGE STABILITY - LOST BUOYANCY METHOD - HEEL AND $\overline{GM}$

SHIP ____________ DATE ____________ PAGE 2

DAMAGE EXTENT ____________ BY ____________

ITEM No.	SOURCE	DESCRIPTION					
$\textcircled{1}$	————————	T, DRAFT BEFORE DAMAGE					
$\textcircled{37}$	$\textcircled{22} + \textcircled{36}\left(0.5 - \frac{\textcircled{29}}{L}\right)$	DRAFT FORWARD AFTER FLOODING (WL_2)					
$\textcircled{38}$	$\textcircled{22} - \textcircled{36}\left(0.5 + \frac{\textcircled{29}}{L}\right)$	DRAFT AFT AFTER FLOODING (WL_2)					
$\textcircled{39}$	DIRECT CALCULATIONS OR CURVES OF FORM	WATERPLANE AREA AT WL_2					
$\textcircled{40}$	DIRECT CALCULATIONS OR CURVES OF FORM	TRANS. MOM. INERTIA OF $\textcircled{39}$ ABOUT C.L.					
$\textcircled{41}$	COMPARTMENT CALCULATIONS	μ_S x LOST WATERPLANE AT WL_2					
$\textcircled{42}$	COMPARTMENT CALCULATIONS	CENTER OF $\textcircled{41}$ FROM C.L. P- S+					
$\textcircled{43}$	COMPARTMENT CALCULATIONS	$\mu_S i_T$ OF $\textcircled{41}$ ABOUT C.L.					
$\textcircled{44}$	$\textcircled{41} \times \textcircled{42}$	————————					
$\textcircled{45}$	$\textcircled{44}^2 / (\textcircled{39} - \textcircled{41})$	————————					
$\textcircled{46}$	$\textcircled{40} - \textcircled{43} - \textcircled{45}$	————————					
$\textcircled{47}$	$\textcircled{5} - \textcircled{6} - \frac{\textcircled{46}}{\textcircled{2}\rho}$	$\overline{BM}$ LOSS					
$\textcircled{48}$	$\frac{\textcircled{1} + \textcircled{22}}{2}$	VERTICAL CENTER OF PARALLEL SINKAGE LAYER					
$\textcircled{49}$	$\textcircled{48} - \textcircled{8}$	$\overline{b\,b_1}$					
$\textcircled{50}$	$\frac{\textcircled{7} \times \textcircled{49}}{\textcircled{2}}$	VCB RISE DUE TO SINKAGE					
$\textcircled{51}$	$\textcircled{36}^2$	$TRIM^2$					
$\textcircled{52}$	$\frac{\textcircled{35} \times \textcircled{51}}{2 \times L \times \textcircled{2}}$	VCB RISE DUE TO TRIM					
$\textcircled{53}$	$\textcircled{47} + 0.17 - \textcircled{50} - \textcircled{52}$	INTACT $\overline{GM}$ FOR 5 cm $\overline{GM}$ DAMAGED					
$\textcircled{54}$	TRIM AND HEEL DIAGRAM	MINIMUM TANGENT TO MARGIN LINE					
$\textcircled{55}$	————————	CORRESPONDING ANGLE OF HEEL					
$\textcircled{56}$	————————	SELECTED ANGLE ϕ					
$\textcircled{57}$	————————	TAN $\textcircled{56}$					
$\textcircled{58}$	$\textcircled{21} + \left(\textcircled{29} + \textcircled{27}\right)\frac{\textcircled{36}}{L}$	HEIGHT WL TO WL_2 IN WAY OF $\textcircled{27}$					
$\textcircled{59}$	$\frac{-12 \times \textcircled{26} \times \textcircled{28} \times \textcircled{58}}{\textcircled{7}}$	CENTER OF NET ADDED BUOYANCY FROM C.L. P- S+					
$\textcircled{60}$	$\textcircled{59} - \textcircled{10}$	TRANSVERSE SHIFT OF BUOYANCY P- S+					
$\textcircled{61}$	$-\textcircled{7} \times \textcircled{60}$	TRANSVERSE MOMENT P- S+					
$\textcircled{62}$	COMPARTMENT CALCULATIONS	MOM. CORRECTION FOR CHANGE IN μ ETC. HEELING THROUGH ϕ P- S+					
$\textcircled{63}$	$\frac{\left\lvert \textcircled{61} + \textcircled{62} \right\rvert}{\textcircled{57} \times \textcircled{2}}$	————————					
$\textcircled{64}$	FIGS. 19, 20 OR DIRECT CALCULATIONS	F					
$\textcircled{65}$	$\textcircled{53} + \textcircled{63} - \frac{\left\lvert \textcircled{64} \times \textcircled{46} \right\rvert}{\textcircled{2}} - 0.05$	INTACT $\overline{GM}$ TO LIMIT HEEL TO $\textcircled{56}$					
$\textcircled{66}$	$\textcircled{53}$ OR $\textcircled{65}$ WHICHEVER IS LARGER	REQUIRED INTACT $\overline{GM}$					
$\textcircled{67}$	$\textcircled{66} + 0.05 - \textcircled{53}$	CORRESPONDING $\overline{GM}$ IN DAMAGE CONDITION					

IF $\textcircled{53}$ IS MORE THAN $\textcircled{65}$, EQUILIBRIUM ANGLE OF HEEL AND RELATED F ARE THOSE WHICH SATISFY EQUATION: $0.05 + F \times \frac{\textcircled{46}}{\textcircled{2}} = \frac{\textcircled{61} + \textcircled{62}}{\textcircled{2} \times \tan\phi}$

Fig. 16 Form for calculation of heel and $\overline{GM}$, lost buoyancy method

$$\frac{-\mu_s a_2 t_2}{A_2 - \mu_s a_2}$$

and

$$I_{T2} = I_{T2CL} + A_2 \times \left(\frac{\mu_s a_2 t_2}{A_2 - \mu_s a_2}\right)^2$$

$$\mu_s i_{T2} = \mu_s i_{T2CL} - \mu_s a_2 t_2^2 + \mu_s a_2 \left(t_2 + \frac{\mu_s a_2 t_2}{A_2 - \mu_s a_2}\right)^2$$

Substituting in Equation (29), one obtains decrease in $\overline{BM}$

$$\overline{BM} - \frac{\left[I_{T2CL} - \mu_s i_{T2CL} - \frac{(\mu_s a_2 t_2)^2}{(A_2 - \mu_s a_2)}\right]}{\Delta/\rho} \quad (20)$$

2. The increase in $\overline{KB}$ due to sinkage is

$$\frac{v' \times \overline{bb}_1}{\Delta/\rho} \quad (21)$$

where $\overline{bb}_1$ = vertical distance from center of lost buoyancy to center of parallel sinkage layer.

3. The increase in $\overline{KB}$ due to trim is

$$\frac{\text{MTm}' \times (\text{trim})^2}{2\Delta L} \quad (22)$$

or in English units (ft),

$$\frac{\text{MTF}_1' \times (\text{trim})^2}{2WL} \quad (22a)$$

As noted in Section 7.5, the present U.S. and international rules require that the $\overline{GM}$ in the damaged condition (displacement taken constant) be at least 5 cm. The required intact $\overline{GM}$ to meet this condition is therefore

$$\overline{BM} - \frac{\left[I_{T2CL} - \mu_s i_{T2CL} - \frac{(\mu_s a_2 t_2)^2}{(A_2 - \mu_s a_2)} + v bb_1\right]}{\Delta/\rho} - \frac{\text{MTm}' \times (\text{trim})^2}{2\Delta L} + 0.05 \quad (23)$$

(*c*) *Unsymmetrical moment and heel.* If the net lost buoyancy is unsymmetrical or if the net added buoyancy between WL and WL_2 is unsymmetrical so that, in either case, there is a transverse shift in buoyancy in sinking and trimming from WL to WL_2, heel will result. In calculating the transverse center of the net added buoyancy, it is necessary to include the effect of trim, which increases the volume swept by the lost area in sinking and trimming from WL to WL_2. Thus TCG of net added buoyancy is

$$\frac{\frac{-100\,(\text{tpcm} + \text{tpcm}_2) \times h_s}{2} \times \frac{(t + t_2)}{2}}{\text{net added buoyancy}} \quad (24)$$

where

tpcm is lost tons per cm at WL
tpcm_2 is lost tons per cm at WL_2
h_s is height WL to WL_2 in way of damage
t is center of tpcm from CL
t_2 is center of tpcm_2 from CL

(The negative sign means that the net added buoyancy is on the opposite side of the centerline from the lost tons per inch.)

Net added buoyancy = net lost buoyancy = v'; $\frac{\text{tpcm} + \text{tpcm}_2}{2}$ = approx tpcm_1 = lost tons per cm at WL_1;

$\frac{t + t_2}{2}$ = approx t_1 = center of tpcm_1 from CL;

h_s may be read from a trim and heel diagram, Fig. 41, or is

$$\text{parallel sinkage} + [\text{LCF}_1' - lcf_1] \times \text{trim}/L$$

The transverse moment due to this shift in buoyancy is then equal to

$$\rho v' \times (\text{TCG of net added buoyancy} - \text{tcg of } v') \quad (25)$$

(*d*) *Required $\overline{GM}$ to limit heel.* For final stages of flooding, the allowable angle of heel, ϕ, generally is that to the margin line but in no case more than the fixed heeling limit prescribed by the applicable rules. Tan ϕ corresponding to heel to the margin line can readily be determined from the trim and heel diagram, Fig. 17.

In heeling through the angle ϕ to the final heeled waterplane, changes in the longitudinal or transverse extent of flooding and/or changes in permeability may occur. These normally may be accounted for as illustrated in Fig. 18, treating the resulting change as producing a transverse moment, which is added to that of Equation (25). In the suggested calculation form, Fig. 16, term (62) provides for this correction. (The accompanying effects on the damaged condition draft and VCB are neglected.)

The heeling moment then is equal to the total transverse moment × cos ϕ. At the same time, as shown in Chapter II, the righting moment at moderate angles may be expressed as

$$\Delta \times (\overline{GM}_R + F\,\overline{BM}_R) \sin\phi \quad (26)$$

where both $\overline{GM}_R$ and $\overline{BM}_R$ are the residual values at WL_2 and F is a factor dependent upon the vessel's

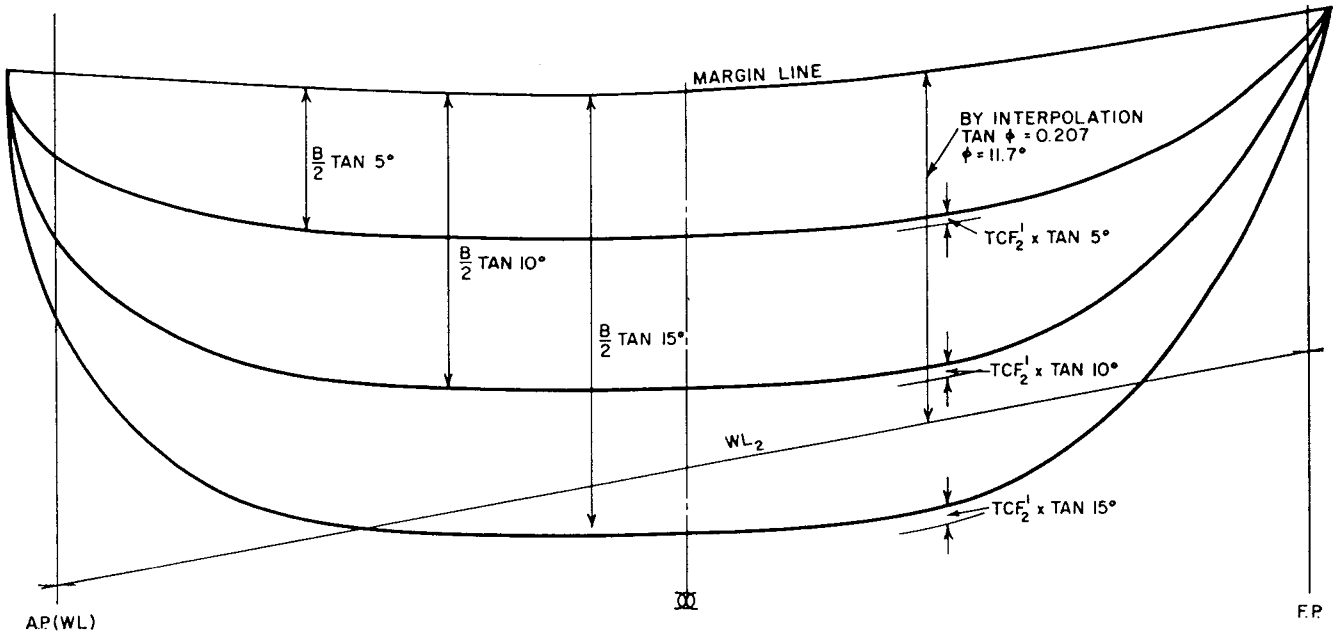


Fig. 17 Trim and heel diagram

proportions and form, such that $F\,\overline{BM}$ is the vertical distance between the zero-heel metacenter and the point P, at which the vertical through the heeled condition center of buoyancy intercepts the centerline. F is, in effect, the ratio of the average change in transverse waterplane inertia, as the vessel heels to any angle ϕ, to the zero heel transverse waterplane inertia. It is generally assumed that the F-value for a damaged ship at any given draft and heel is the same as for the intact ship at the same draft and heel. This assumption is considered to be sufficiently accurate for ordinary merchant ship forms, at moderate angles of heel, and within ordinary operating ranges of beam-draft ratio. It may not be valid at very light drafts or for unusual hull forms. In applying this assumption, it is also necessary to account for the effect of any local changes in lost waterplane as the vessel heels. In the case of lost-buoyancy calculations this is done as illustrated in Fig. 18 and the related text. If the trim-line added-weight procedure is used, the calculations of flooding water and moment automatically include the effect of any such changes.

Figs. 19 and 20 give approximate F-values for the average ship form, without tumble-home or flare amidships and having a midship coefficient of about 0.96 or greater. For heels not immersing the deck edge or rolling the bilge side tangency out, the solid line portions of these figures give values which are sufficiently accurate for usual intact or damage stability calculations. The dotted line portions are progressively likely to be less accurate as they depart from the solid line portions, and should only be used without further check when the resulting values indicate an appreciable stability margin (Prohaska, 1961).

Equating terms, the intact $\overline{GM}$ necessary to limit heel to any angle ϕ is given by:

$$\overline{GM}\text{ loss} + \frac{\text{transverse moment}}{\Delta \times \tan\phi} - F\,\overline{BM}_R \quad (27)$$

where $\overline{GM}$ loss = value from equation (23) − 0.05.

The required intact $\overline{GM}$ then is that determined by Equation (23) or (27), whichever is larger.

The required initial $\overline{GM}$s at various drafts are usually plotted along with the available $\overline{GM}$s in the various operating conditions. An example is shown in Fig. 21,

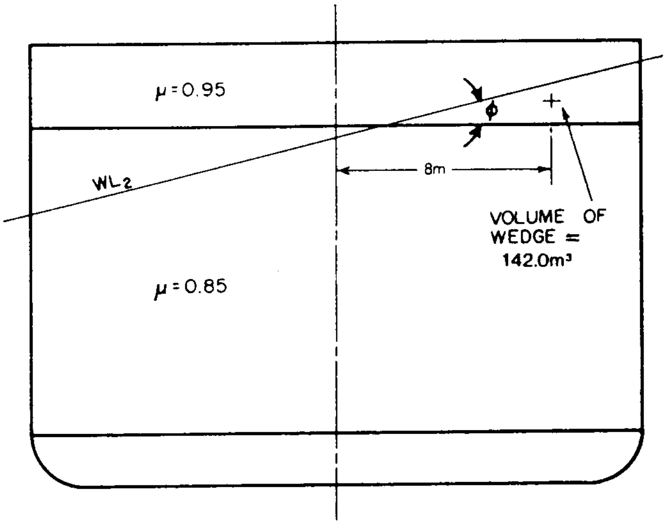


Fig. 18 Transverse moment due to heel into a level of higher permeability (142(0.95-0.85)1.025 × 8 = 116 t-m)

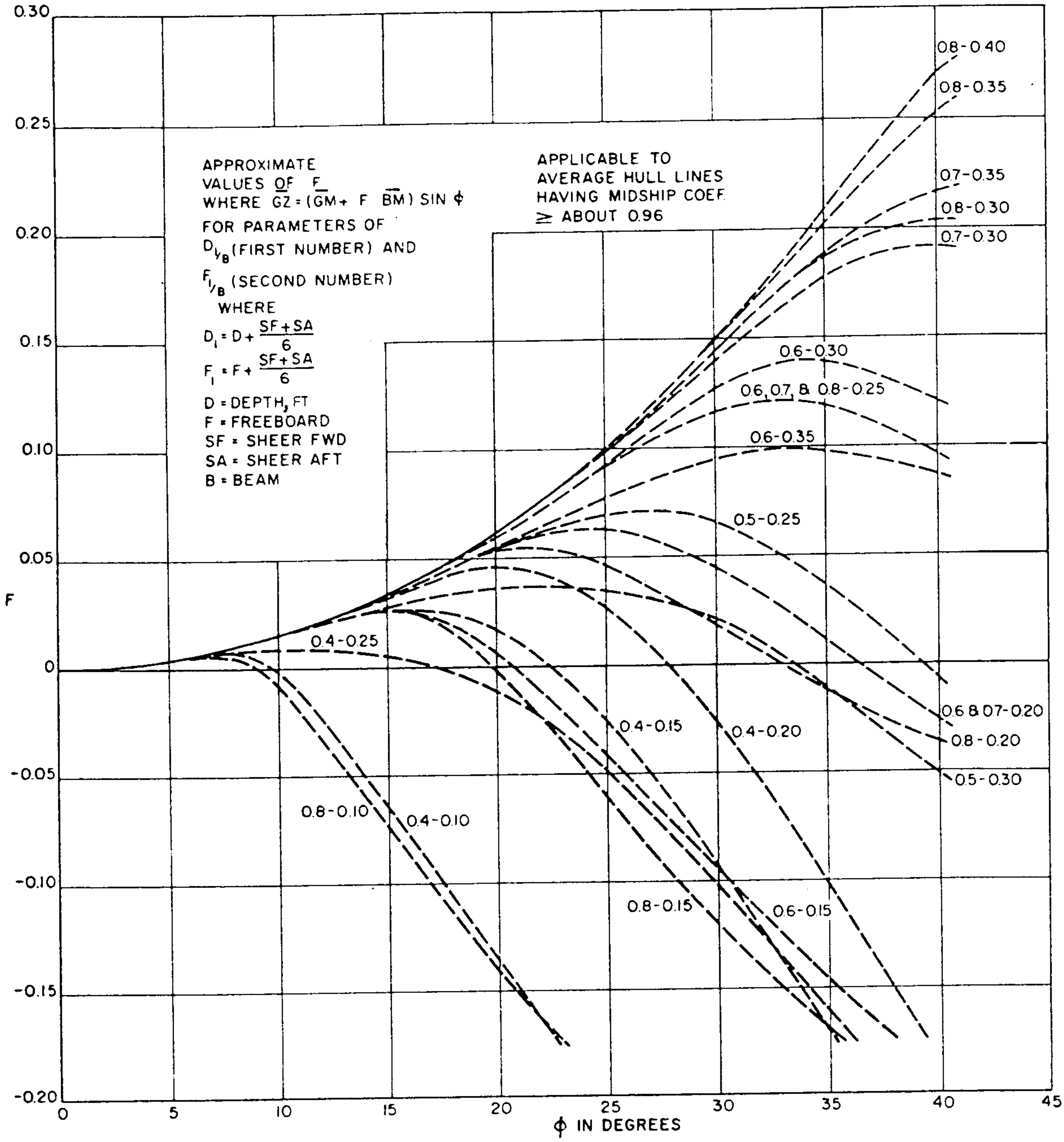


Fig. 19 Approximate values of F, where $\overline{GZ} = (\overline{GM} + F\,\overline{BM}) \sin \phi$

which indicates whether the available $\overline{GM}$ in these conditions equals or exceeds the required $\overline{GM}$. Obviously if they all do not, the vessel does not meet the criterion. See also Chapter II.

4.7 Trim-Line Added-Weight Method. The version of this method described in the following text, including Section 4.5, provides sufficiently accurate results for all usual conditions and is more versatile in this respect than the lost buoyancy method. In addition, it is believed generally to involve less computation than trim-line added-weight calculations based upon direct use of Bonjean curves. However, if flooding involves extreme conditions of trim and heel combined, the most accurate results can be attained by obtaining displacements and moments by direct use of Bonjean curves. In such case, it is necessary that these curves be provided for both upright and heeled conditions, and that they include not only the usual area values but also transverse and vertical moment values and, for the upright condition, half-breadths cubed. If this is done, the necessary related calculations differ in detail but agree fully in principle with those described herein.

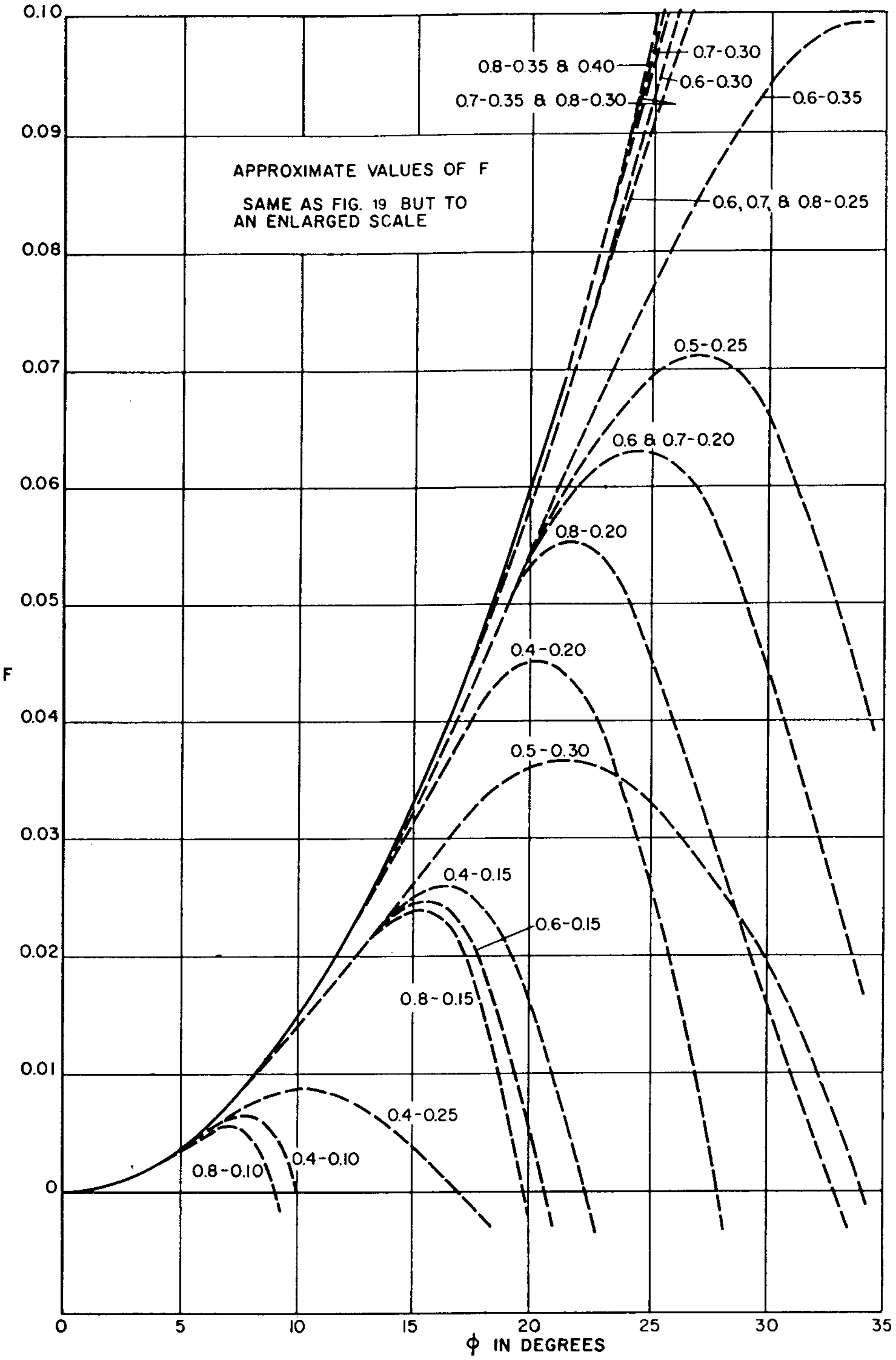


Fig. 20 Approximate values of F, where $\overline{GZ} = (\overline{GM} + F\overline{BM}) \sin \phi$

In using the method hereinafter described, all ship hydrostatic values, except where otherwise specially noted, are for an assumed undamaged ship at the applicable draft and trim. If conditions involving appreciable trim exist, convenience and accuracy favor the use of curves of form which give the effective LCF, $\overline{KM}$, $\overline{KB}$, and TPcm values for trims forward and aft as well as level trim. It is usually adequate for this purpose to calculate displacement, $\overline{KM}$, $\overline{KB}$, and TPcm versus mean draft for fixed values of trim, say $L/40$, forward and aft, depending upon interpolation or cross-plotting for intermediate values. The trimmed condition effective LCF is taken as the longitudinal position at which the trimmed waterplane is the same

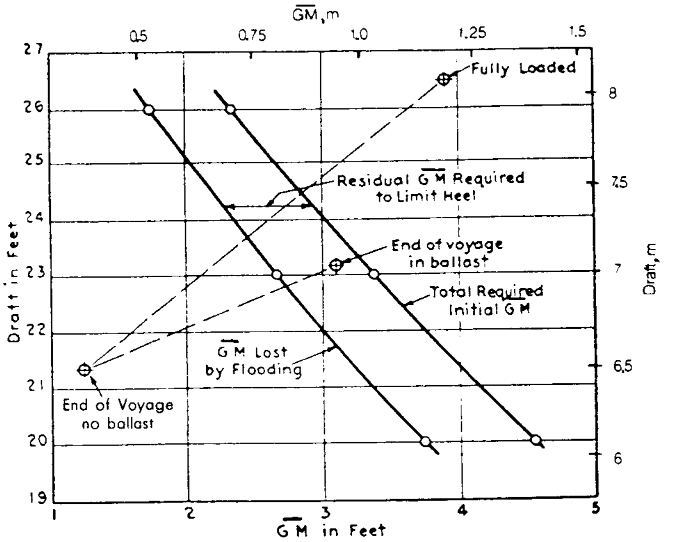


Fig. 21 Diagram Showing Available $\overline{GM}$ at Beginning and End of Voyage and Required Initial $\overline{GM}$

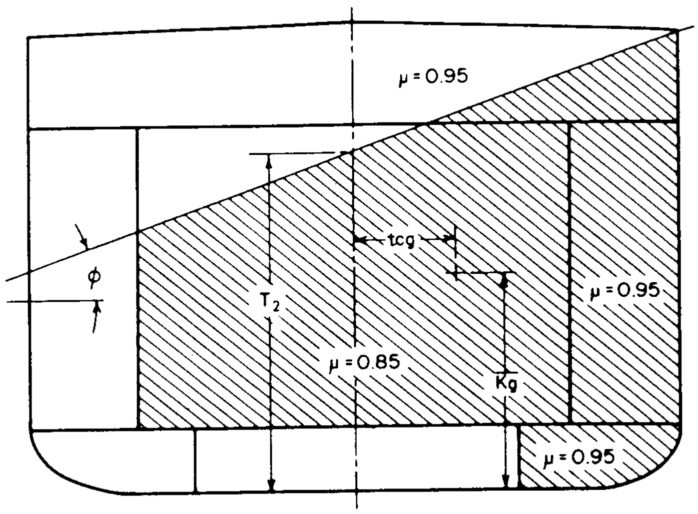


Fig. 22 Section through flooded compartment

distance above the baseline as the level trim draft for the same displacement. That is to say, the effective LCF of any waterplane equals the difference between the amidships draft for that waterplane and the corresponding level trim draft × the cotangent of the trim. Thus, the final plot of displacement versus draft at LCF shows a single line for all trims. At the same time, the calculated mean draft points for the $\overline{KM}$, $\overline{KB}$, and TPcm curves are shifted vertically so that these values are also plotted on the basis of the draft at the LCF. Unless specifically excepted, all drafts used in this method are at the LCF. Moment to trim 1 cm is assumed to be constant over the range of trim concerned and the plotted value may be based either upon the average calculated shift of LCB with trim or upon the level trim waterplane inertia.

A mean transverse section similar to Fig. 22 is prepared for each damaged compartment to be considered. If the compartment is long, has appreciable variation with length, or contains longitudinal discontinuities, convenience and accuracy may require that it be separated into two or more parts. In judging the need for doing this, the use of mean sections will result generally in underestimating the heeling moment due to free surface by less than 1 percent if the breadth of the smaller end is 85 percent of that of the larger, while a breadth ratio of 75 percent may result in an underestimate of about 2 percent.

Taking into account the assumed extent of damage and the allocation of the various spaces represented by the mean transverse section, a summation of the areas and moments of each portion of the section, each multiplied by a suitable constant depending upon the permeability and the flooded length, then gives the mass of flooding water and the moments of flooding water. This integration is performed for the expected range of drafts in way of the compartment and for at least two heeled conditions, usually 7 and 15 deg, for which mass of flooding water w/g and virtual vertical moment of flooding water $\left[w/g\left(\overline{Kg} + \dfrac{\text{tcg}}{\tan\phi}\right)\right]$ are obtained. If righting-arm curves in the damaged condition will be required, calculations are also made for additional angles of heel to cover the necessary range. If the amount of unsymmetrical flooding is small and it therefore seems likely that the $\overline{GM}$ necessary to limit heel may be less than that required to provide a 5-cm (2-in) positive $\overline{GM}$ upright in the damaged condition, calculations are also made for the zero-heel condition, in which case the quantities which need to be determined are the mass of flooding water w/g, vertical moment of flooding water $(w/g)\ \overline{Kg}$, net lost waterplane transverse moment of inertia about centerline $\mu_s i_T$, net lost $\text{TP}_{\text{cm}}\ \rho\mu_s a/100$ (or tons per m, $\rho\mu_s a$), and center of same from centerline (tca).

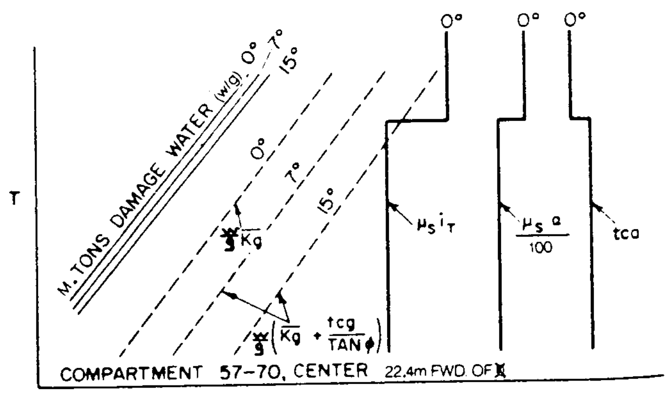


Fig. 23 Plot of damage water quantities with heel

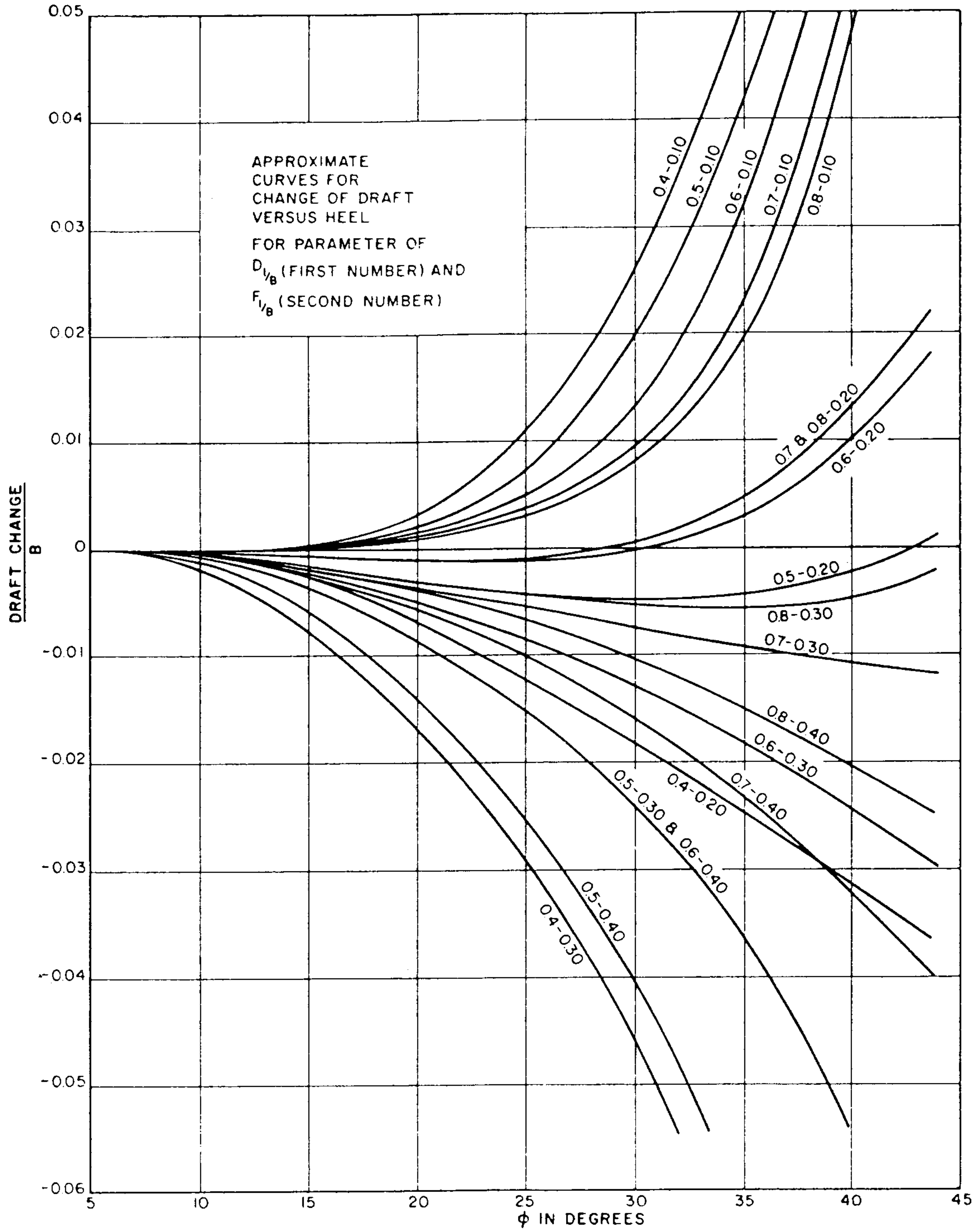


Fig. 24 Change of draft versus heel

In making these calculations, the mass of flooding water, and related quantities are taken to correspond to $\Sigma\mu v\rho$ for all breached spaces up to the assumed final flooding line less the total mass of liquids assumed to be in such spaces before damage. However, where tanks are low in the ship, the most severe condition may be one in which they are not breached and flooding occurs only above them. Where doubt is considered to exist as to the outcome, calculations should be made assuming such tanks both breached and nonbreached. The nonbreached condition corresponds to the zero permeability condition called for by Section 7.5. These calculations are performed and the data are plotted for each section as illustrated in Figs. 22 and 23.

(*a*) *Draft and trim.* The ship is assumed at a damaged condition draft, T_2. At this draft and an assumed level trim, displacement, LCF, and moment to trim 1 cm are read from the curves of form; and mass of flooding water and lcg of flooding water are read from the curves for the applicable damaged compartment(s). (Because the effects of compartment shape and of trim are partially compensatory, sufficient accuracy is normally attained by assuming the lcg of a compartment or of a part to be at its midlength.)

A first approximate value for the trim due to flooding is

$$\text{Trim, cm} = \frac{(w/g)\,(\overline{⊗g} - \overline{⊗F})}{100\ \text{MTcm}} \tag{28}$$

or in English units,

$$\text{Trim, ft} = \frac{w(\overline{⊗g} - \overline{⊗F})}{12 \times \text{MTI}} \tag{28a}$$

Since trim increases the draft in way of the damage and therefore the amount of flooding water, the actual trim due to the damage will, in general, be more than this first approximation. At average damaged condition drafts, it may be about 10 percent more. With this in mind, a trimmed waterline corresponding to the vessel LCF draft, T_2 is assumed.

A trim and heel diagram similar to Fig. 17, but showing both the LCF curve or curves and the longitudinal center or centers of flotation of the damaged compartments, is used. By placing the assumed trimmed waterline on the diagram, the angle of heel to the margin line and the draft at the center of the damaged space or spaces, or of each section thereof, can be read off. Since the compartment characteristics are plotted on a basis of centerline draft, no draft correction for TCF of damaged waterplane is made.

Using the compartment curves, the values corresponding to these damaged space drafts are then totalled for the space or spaces included in the damage. If the unsymmetrical part of the flooding is small, i.e., if a large portion of the heeling moment results from the transference of wedges as the vessel heels, the $\overline{GM}$ necessary to provide a 5-cm (2-in) positive $\overline{GM}$ in the damaged condition may be more than that to limit heel. If this is considered likely, calculations are made both for a zero heel condition and for one or more assumed heeled conditions. (In dealing with the zero heel condition, transverse moment is assumed to be eliminated; i.e., as would be the case if weights elsewhere in the ship were shifted to equalize the heeling moment.)

In either case the amount of flooding water subtracted from the displacement at T_2 then gives the displacement before damage, and the corresponding LCF draft before damage, T, is read from the curves of form.

For angles of heel up to and including 15 deg the change in draft accompanying heel is normally disregarded. However, for higher angles of heel, where the deck edge is appreciably immersed or the bilge emerges, the change may be considerable. Fig. 24, which is based upon the stability model tests reported in Russo & Robertson (1950), provides a means of approximating this change, and thus improving the accuracy of the calculations. The change in draft determined from this figure is applied to T_2, the centerline LCF draft for the assumed trim line. The correct displacement and other hydrostatic properties corresponding to T_2 are then determined by entering the curves of form with the resulting amended draft, not T_2.

For purposes of calculating trim it is usually assumed that the mean emergence draft is equal to the mean between the assumed damage condition draft, T_2, and the mean of the drafts before damage determined for the zero heel and for the limiting heel conditions. It is assumed that addition of a weight equal to the flooding water at the level or normal trim LCF corresponding to this mean emergence draft would result in sinkage from T to T_2 without any change in trim. The trimming lever is therefore taken as the distance between this LCF and the lcg of flooding water, and the trim recomputed by Equation (28). The difference between this computed trim and the assumed trim is the trim before damage. If this trim before damage is within the normal operating range for that draft it may be considered satisfactory, having regard, at the same time, that trim may be more critical when heeling is restricted by damaged condition freeboard. With a little experience in the selection of assumed trims, agreement within 30 cm (about 1 ft) can usually be obtained, and this is entirely adequate.

The calculation of required initial $\overline{GM}$ is then carried out in accordance with the fundamental relationships given in Section 3.3. See Figs. 25 and 26.

4.8 Stability during Intermediate Flooding. During the intermediate stages of flooding the water is continually flowing into the damaged compartment. Hence, the added weight approach is applicable, with allowance for the free surface of the water that has flowed in.

Conditions during intermediate flooding may vary widely. When colliding vessels immediately separate after a collision, the dynamic effect of the roll of the struck vessel as a result of the impact, plus the surge of water into the damaged space, conceivably may be quite unfavorable. On the other hand, if the striking vessel remains engaged with the struck vessel for a time, it may more or less restrain that vessel during the period of intermediate flooding.

In recognition of these extremes, as well as the practical requirements of using known quantities in the calculations, the following assumptions are used in intermediate flooding:

(*a*) The vessel is assumed to be in static equilibrium

DAMAGE STABILITY - TRIM LINE ADDED WEIGHT METHOD - DRAFT AND TRIM - BASIC DATA

SHIP ______________ DATE ______________ PAGE 1

DAMAGE EXTENT ______________ BY ______________

ITEM No.	SOURCE	DESCRIPTION						
(1)	ASSUMED	T_2 LCF DRAFT IN DAMAGED CONDITION						
(2)	CURVES OF FORM	GROSS DISPLACEMENT, Δ AT (1)						
(3)	CURVES OF FORM	LCF AT (1) AND LEVEL TRIM F+ A−						
(4)	CURVES OF FORM	MOM. TO TRIM ONE m AT (1)						
(5)	DAMAGED COMPARTMENT CURVES	TONNES FLOODING WATER, $\frac{W}{g}$ AT (1) AND ZERO HEEL						
(6)	DAMAGED COMPARTMENT CURVES	lcg OF (5) F+ A−						
(7)	(6) - (3)	APPROXIMATE TRIM LEVER F+ A−						
(8)	(5) x (7)/(4)	APPROXIMATE TRIM F+ A−						
(9)	ABOUT 1.1 x (8)	ASSUMED TRIM F+ A−						
(10)	CURVES OF FORM	EFFECTIVE LCF AT (1) FOR (2) AND (9) F+ A−						
(11)	CURVES OF FORM	$\overline{KM}$ FOR (2) AND (9)						
(12)	CURVES OF FORM	$\overline{KB}$ FOR (2) AND (9)						
(13)	CURVES OF FORM	TONNES PER m FOR (2) AND (9)						
(14)	(1) + (9) $\left(0.5 - \frac{(10)}{L}\right)$	DAMAGED CONDITION DRAFT FORWARD						
(15)	(1) − (9) $\left(0.5 + \frac{(10)}{L}\right)$	DAMAGED CONDITION DRAFT AFT						
(16)	TRIM AND HEEL DIAGRAM	MINIMUM TANGENT TO MARGIN LINE						
(17)	————————	CORRESPONDING ANGLE OF HEEL, DEG.						
(18)	————————	SELECTED ANGLE ϕ, DEG.						
(19)	TRIM AND HEEL DIAGRAM	T_d DRAFT (S) AT DAMAGED SPACE (S)						
(20)	DAMAGED COMPARTMENT CURVES	TONNES FLOODING WATER, $\frac{w}{g}$ AT (19) AND ZERO HEEL						
(21)	DAMAGED COMPARTMENT CURVES	TONNES FLOODING WATER AT (19) AND (18)						
(22)	DAMAGED COMPARTMENT CURVES	lcg OF (20) F+ A−						
(23)	DAMAGED COMPARTMENT CURVES	lcg OF (21) F+ A−						
(24)	DAMAGED COMPARTMENT CURVES	$\frac{w}{g}\overline{Kg}$ AT (19) AND ZERO HEEL						
(25)	DAMAGED COMPARTMENT CURVES	$\mu_s i_T$ AT (19) AND ZERO HEEL						
(26)	DAMAGED COMPARTMENT CURVES	$\mu_s a \rho$ AT (19) AND ZERO HEEL						
(27)	DAMAGED COMPARTMENT CURVES	tcg AT (19) AND ZERO HEEL P− S+						
(28)	DAMAGED COMPARTMENT CURVES	$\frac{w}{g}\left(\overline{Kg} + \frac{tcg}{\tan\phi}\right)$ AT (19) AND (18)						
(29)	(2) - (20)	DISP. BEFORE DAMAGE FOR ZERO HEEL						
(30)	(2) - (21)	DISP. BEFORE DAMAGE FOR (18)						
(31)	CURVES OF FORM	DRAFT BEFORE DAMAGE FOR ZERO HEEL						
(32)	CURVES OF FORM	DRAFT BEFORE DAMAGE FOR (18)						

NOTE: IN ALL CASES TONNES FLOODING WATER, $\frac{W}{g} = \Sigma \mu \rho v$ FOR ALL BREACHED SPACES, LESS TONNES OF LIQUIDS ASSUMED TO BE IN SUCH BREACHED SPACES BEFORE DAMAGE.

Fig. 25 Form for calculation of draft and trim, added-weight method

DAMAGE STABILITY - TRIM LINE ADDED WEIGHT METHOD - TRIM, HEEL AND $\overline{GM}$

DATE ____________ PAGE 2

SHIP ____________ BY ____________

DAMAGE EXTENT ____________

ITEM No	SOURCE	DESCRIPTION						
(31)	PAGE 1	DRAFT BEFORE DAMAGE FOR ZERO HEEL						
(33)	(2 × (1) + (31) + (32))/4	MEAN EMERGENCE DRAFT						
(34)	CURVES OF FORM	LCF AT (33) AND LEVEL TRIM F+ A−						
(35)	(22) − (34)	TRIM LEVER FOR ZERO HEEL F+ A−						
(36)	(20) × (35)/(4)	COMPUTED TRIM FOR ZERO HEEL F+ A−						
(37)	(9) − (36)	TRIM BEFORE DAMAGE FOR ZERO HEEL F+ A−						
(38)	(26) × (27)	TRANS. MOM. OF NET LOST AREA						
(39)	$(38)^2$	————————						
(40)	(13) − (26)	NET TONNES PER m						
(41)	(39) / (40)	————————						
(42)	((25) + (41))/(2)	BM LOSS FOR (2) AND (9)						
(43)	(11) − (42)	NET KM FOR (2) AND (9)						
(44)	$\frac{(2) \times (43) - (24)}{(29)} - 0.05$	MAX. ALLOWABLE KG BEFORE DAMAGE						
(45)	CURVES OF FORM	$\overline{KM}$ AT (31) FOR (29) AND (37)						
(46)	(45) − (44)	INTACT GM FOR 5 cm $\overline{GM}$ DAMAGED						
(32)	PAGE −1	DRAFT BEFORE DAMAGE FOR (18)						
(47)	(23) − (34)	TRIM LEVER FOR (18) F+ A−						
(48)	(21) × (47)/(4)	COMPUTED TRIM FOR (18) F+ A−						
(49)	(9) − (48)	TRIM BEFORE DAMAGE FOR (18) F+ A−						
(50)	————	TANGENT (18)						
(51)	————	SINE (18)						
(52)	FIGS. 19-23 OR DIRECT CALCULATIONS	F FOR (18)						
(53)	(11) − (12)	$\overline{BM}$ FOR (2) AND (9)						
(54)	(11) + ((52) × (53))	$\overline{KP}$						
(55)	(2) × (54) / (30)	————————						
(56)	(28) / (30)	————————						
(57)	(55) − (56)	MAX ALLOWABLE $\overline{KG}$ BEFORE DAMAGE						
(58)	CURVES OF FORM	$\overline{KM}$ AT (32) FOR (30) AND (49)						
(59)	(58) − (57)	INTACT GM TO LIMIT HEEL TO (18)						
(60)	(46) OR (59) WHICHEVER IS LARGER	REQUIRED INTACT $\overline{GM}$						

IF (46) IS MORE THAN (59), EQUILIBRIUM ANGLE OF HEEL WHICH CORRESPONDS THERETO, RELATED F, AND $\frac{w}{g}$ ARE THOSE WHICH SATISFY THE EQUATION: $(11) + F \times (53) - (44) = \dfrac{\frac{w}{g}\left(K_g + \frac{tcg}{\tan\phi}\right) - \frac{w}{g} \times (44)}{(2)}$

(WHERE $\frac{w}{g}$ IS BETWEEN (20) AND (21))

Fig. 26 Form for calculation of heel and $\overline{GM}$, added-weight method

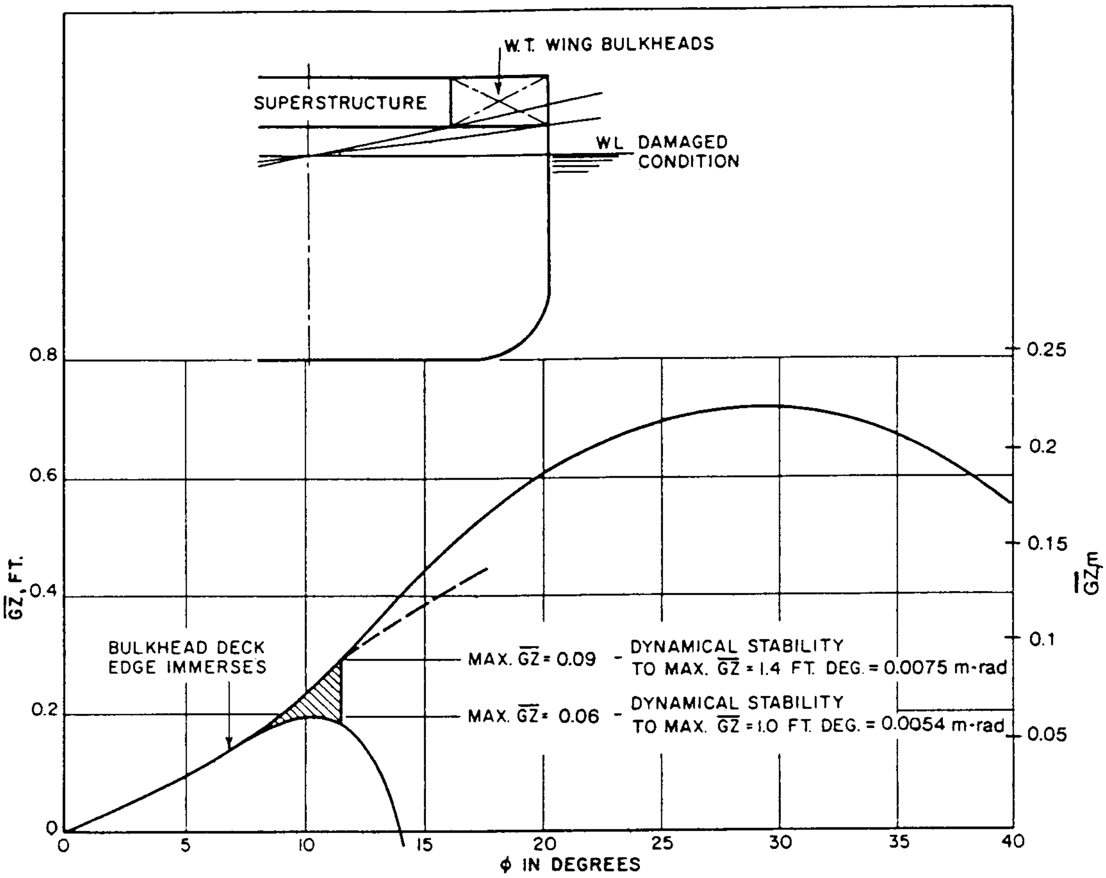


Fig. 27 Effect of watertight wing bulkheads in superstructure

For this example, $B = 25$m; freeboard after damage $= 1.5$m; $\overline{GM}$ after damage $= 0.3$m

at every stage of flooding, with the flooding water surface parallel to, but at a lower level than the surface of the sea.

(b) In the case of unsymmetrical flooding involving spaces which are cross-connected by pipes, ducts, or flooding plugs, it is normally assumed that the flooding water in the damaged wing space reaches sea level, and the vessel heels accordingly, before any equalization occurs.

(c) Wing spaces which are freely interconnected by large unobstructed openings are assumed to equalize as they flood.

During intermediate flooding, heel may occur either as a result of negative $\overline{GM}$ or from unsymmetrical flooding. Since the condition is transient, some heel is acceptable provided the accompanying range of stability and maximum righting arm include a sufficient margin against capsizing.

The matter of just how much margin is "sufficient" is rather indeterminate. There may be considerable difference in required margin, depending, for example, on whether equalization takes place in 1.5 min or 1.5 hr (see 7.6). In situations such as this where the safety of people and property are involved, the prudent naval architect will endeavor to arrange compartments so that equalization is either not required or can be at-

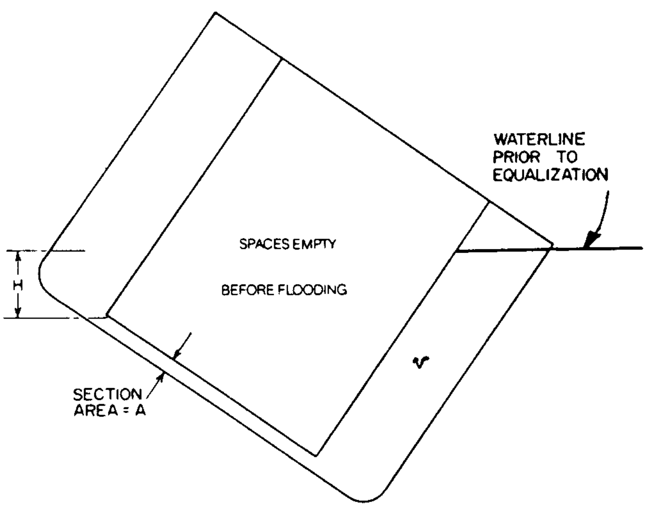


Fig. 28 Equalization of wing tanks

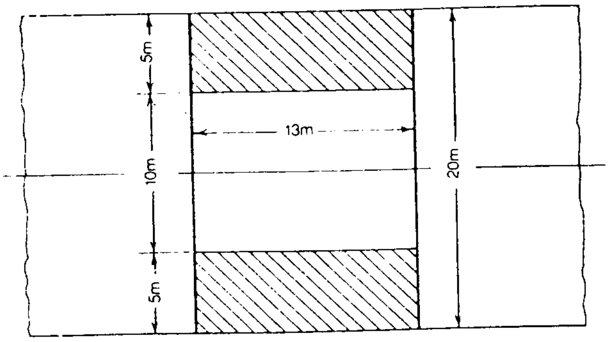


Fig. 29 Assumed wing tanks for free surface calculation

tained quickly and will provide, in all stages of equalization, a range and amplitude of righting arm close to that required by the survival criteria. In judging this, the righting arm curve should be assumed to go to zero at the point where downflooding through openings in the bulkhead deck can occur. It is therefore a desirable design feature to have such openings as far inboard as practicable.

It is frequently practicable to have the wing bulkheads in spaces above the bulkhead deck watertight; the beneficial effect of such bulkheads has been referred to in Section 2.2, as illustrated in Fig. 27. At the point where flooding reaches the inboard lower corners of such bulkheads, the righting arm curve theoretically drops to the lower curve, corresponding to the bulkhead deck, and is not reversible. However, where there is a fore and aft passage bulkhead at the inboard edge of the wing bulkhead, outboard extension of flooding may be retarded enough so that the effective dynamic value of $\overline{GZ}$ approaches that indicated by the dotted line. This gain cannot be evaluated specifically, but does have the effect of narrowing the necessary margin between the statical heeling arm and the peak $\overline{GZ}$. It is obviously desirable that the wing bulkheads extend as far inboard, and that their con-

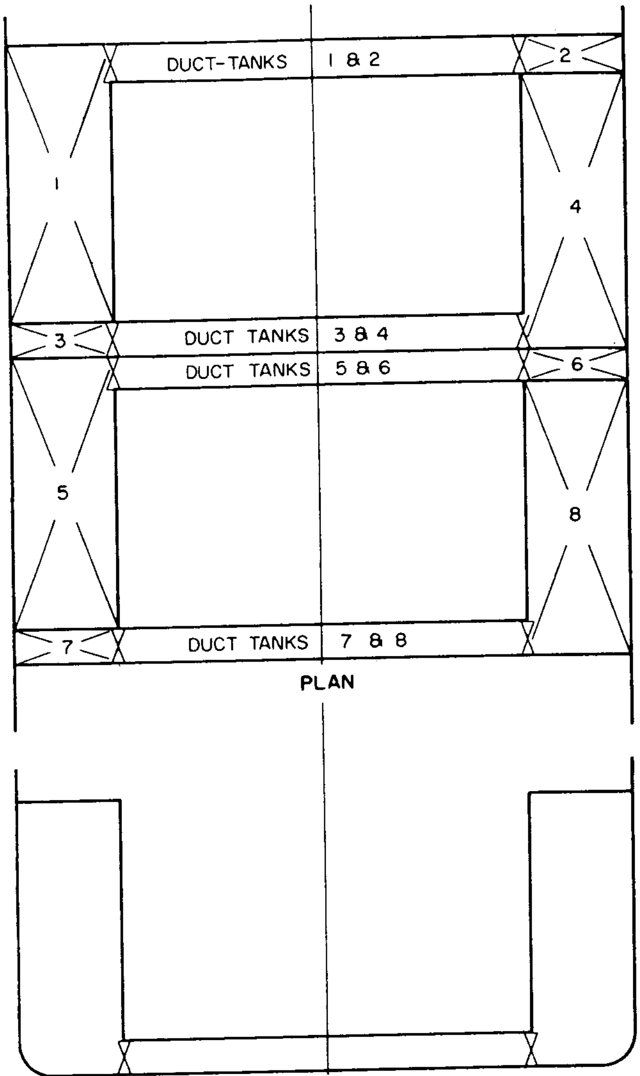


Fig. 32 Alternative cross-connection of wing tanks

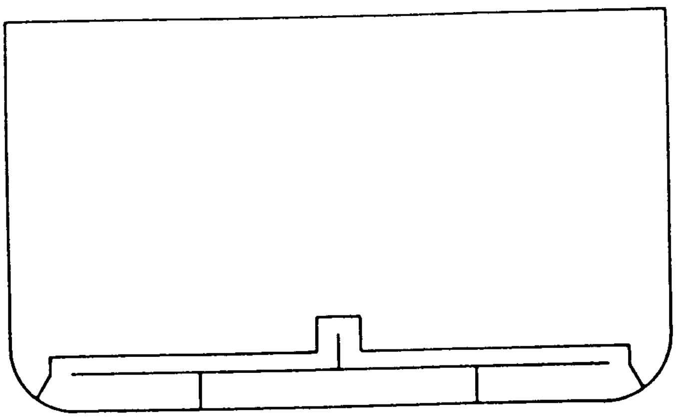


Fig. 30 Cross-connection of double-bottom spaces

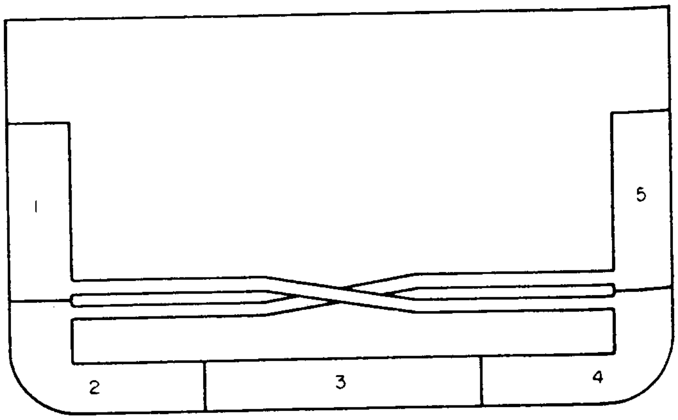


Fig. 31 Cross-connection of wing tanks

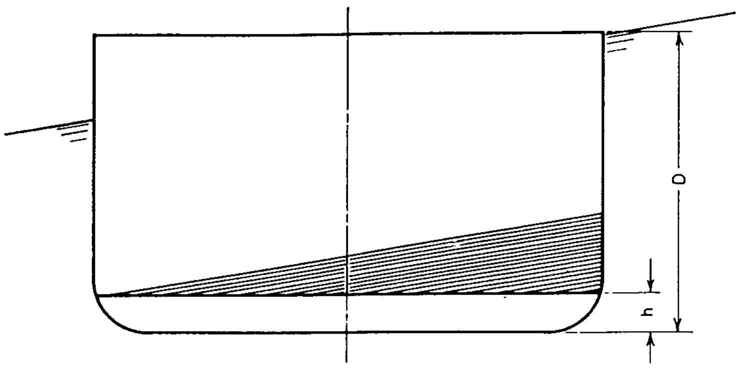


Fig. 33 Intermediate flooding

struction and arrangement be as effective, as is practicable.

When port and starboard spaces are cross-connected to minimize or eliminate unsymmetrical buoyancy, such spaces may be assumed to equalize concurrently with flooding on the damaged side only if they are connected by large unobstructed openings such as open passages or cofferdams, as illustrated in Fig. 28.

When spaces are cross-connected, equalization time, in seconds, may be estimated by the following formula set forth by G. Solda (1961):

$$t = \frac{2v}{fA(2gH)^{1/2}} \tag{29}$$

where

v is total volume of unequalized flooding, or of liquid to be dumped
f is flow coefficient (0.65 may generally be assumed if connection is short and direct and is fitted with not more than one full area gate valve or equivalent)
A is sectional area of equalizing duct or dump line
H is net head at beginning of equalization or dumping

In English units, this reduces to,

$$t = \frac{v}{157\ AH^{1/2}} \text{ min} \tag{30}$$

Cross connections between tanks present a different problem. Such connections, if of ordinary design and open, may greatly increase the free-surface effect of liquids in the tanks. For example, suppose that the dimensions of the tanks were as shown in Fig. 29. The combined moment of inertia of the surfaces of these two tanks, about longitudinal axes through their respective centers of area, is

$$\frac{2 \times 13 \times (5)^3}{12} = 270.8 \text{ m}^4$$

If the tanks are cross-connected, their surfaces will constitute a single surface the center of area of which is on the centerline of the ship. The moment of inertia about this axis is

$$\frac{13 \times [(20)^3 - (10)^3]}{12} = 7583 \text{ m}^4$$

which is 28 times as much as when the tanks were separate. If the ship should be flooded in compartments other than those containing the cross-connected wing tanks, their large free surface would still exist in the flooded ship. Therefore, a correspondingly increased $\overline{GM}$ before free-surface correction would be required to insure sufficient residual stability after flooding. See Chapter II.

Such operational free-surface effects may be eliminated by providing valves in the cross connections or by using special automatic tank and cross-connection arrangements which permit liquid transfer from a damaged tank to an intact one on the other side, without resulting in appreciable transfer between undamaged tanks.

Where valves are fitted, it is usual to specify that these be maintained closed at all times except when opened and reclosed for drill and test purposes, or when a valve or valves may actually be required to be opened to equalize flooding. This is effective, but is subject to the risk that, in time of emergency, a valve may either not be opened or may be unnecessarily and wrongly opened to the detriment of stability.

No attempt is made here to discuss special automatic tank arrangements and cross connections, since there is a variety of ways in which a designer may reduce the amount of unsymmetrical intact buoyancy and yet maintain satisfactory intact stability. Figs. 30, 31, and 32 illustrate ways of doing this.

With modern computer techniques (Section 5), it is relatively easy to check the ship's actual heel by the calculation of residual righting arms with varying amounts of water in the compartment at levels of, for example, 1/16, 1/3 and 2/3 of the distances from the top of the double bottom to the intact waterline. See Section 5. From the righting arm curve, the positive or negative $\overline{GM}$ is immediately available.

In the case of symmetrical flooding, the vessel may heel due to negative $\overline{GM}$ in the early stages of flooding. The required intact $\overline{GM}$ to limit heel so as not to immerse any particular reference point, such as the margin line, generally is greatest for the time in flooding at which the double bottom just becomes covered, as illustrated in Fig. 33.

Section 5
Subdivision and Damage Stability Calculations by Computer.

5.1 General. Computer programs are now widely available throughout the world to calculate subdivision and damage stability. In the United States the program most widely used is the Ship Hull Characteristics Program (SHCP). The subroutines available in the basic program are discussed here. Many users, i.e., government agencies, design agents, shipyards, for example, have developed additional subroutines to further reduce manual labor. Thus the use of computers makes possible a more comprehensive and rigorous analysis than would otherwise be possible.

In addition to the Floodable Length Program described below, a Trim Lines Sub-program calculates final damaged ship drafts and trim after flooding of specific compartments or groups of compartments at specified permeabilities. A Limiting Drafts Sub-program determines the maximum drafts forward and aft to which a ship may be loaded prior to flooding and still survive when a specific compartment or group of compartments is flooded.

A fundamental limitation of computers is that the output is only as good as the input and great care and forethought are necessary in subdivision and damage stability calculations to insure that all relevant flooding combinations are included. Not only must longitudinal, transverse and horizontal flooding be carefully defined, but all conditions affecting weight and volume, such as longitudinal, transverse and horizontal changes in permeability, if any, must be allowed for. Dimensioned sketches should be prepared and retained as records of assumed flooding on which input data are based.

In future it may be expected that hand-held and/or microcomputers, which have been programmed for other naval architectural calculations, will be applied to flooding and damage stability.

5.2 Floodable Length. The method used by the Ship Hull Characteristics Program (NAVSEA, 1976) to calculate floodable length by computer is quite different from the method of manual calculation described in Section 4. Instead of using trim lines, SHCP divides the length of the hull into a user-specified number of equal intervals (minimum length LBP/40), and taking each of these points in turn as a center of damaged length, calculates by an iterative process the resulting equilibrium draft and trim, varying the damaged length until the equilibrium waterline just touches the margin line. The damage lengths thus determined represent points on the floodable length curve.

Plotter routines are available which quickly plot curves of floodable length at any number of varied permeabilities.

5.3 Damage Stability. The object of the Damage Stability Sub-program is to calculate righting arm curves for the ship after damage and flooding of various compartments and combinations of compartments. Another sub-program calculates Cross Curves after damage, if desired.

Table 1—SHCP Computer Print Out—One Damage Condition

DAMAGED STATICAL STABILITY CALCULATIONS

CONDITION 2 COMPARTMENTS INCLUDED 40 41 42 43 44 45 46 47 900 901 902 903 904

NET DAMAGED SHIP PROPERTIES

DISP	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
2125.96	−7.404	0.0	0.0	−0.525	−0.525	15.705	−7.720	24.110	−3.863
			2.86	0.676	−0.110	15.716	−7.720	24.106	−3.857
			10.00	3.687	0.951	15.837	−7.717	24.061	−3.793
			15.00	5.845	1.759	16.016	−7.718	24.056	−3.774
			25.00	9.799	3.115	16.506	−7.684	24.193	−3.261
			35.00	13.241	4.178	17.118	−7.532	24.591	−1.431

(a) General. In calculating damage stability using the basic SHCP program, it will be realized that the Ship Data Table and all of the basic hydrostatic data for the hull form have already been entered into the computer and the subroutine simply calls on the computer for information from this data base. The user inputs the offsets of all compartments and/or groups of compartments as well as the appropriate permeabilities, and the assumed pole height. For each damaged condition and each heel angle the program then calculates the volume and LCB of the damaged ship iteratively at varying draft and trim until the net remaining intact portion of the damaged ship has displacement and LCB consistent with the design intact condition.

The machine then calculates the righting arm (RA); the transverse center of buoyancy (TCB), the vertical center of buoyancy (VCB) and the longitudinal center of buoyancy (LCB) for the vessel in each damaged condition at all angles of heel. The user designates the angles (up to 10) so as to ensure that he gets results at points closely spaced above and below changes such as chines, knuckles, and deck edges.

A typical computer printout of the results for one condition is given in Table 1. The numbers shown in the line opposite "Condition" are, of course, keyed to the designations established for the compartment or compartments damaged. Similar data on the intact ship and on individual compartments can also be printed out if desired. Provided input data and instructions are complete and accurate, the results of the computer calculations are more accurate than those of the manual method. This is particularly true for ships of unusual form, or where sinkage, trim and heel involve immersion of decks or where changes in permeability occur. This is because the computer procedure involves the direct integration of all intact and flooded areas and volumes up to the damaged waterline.

(b) Residual $\overline{GM}$, Heel and Freeboard. To determine compliance with survival criteria specifying minimum $\overline{GM}$, maximum heel and minimum freeboard from the data given by the basic SHCP program a manual analysis of the data in the computer printout must be made. This requires:

1. The correction of the righting arm values for the actual $\overline{KG}$ of the ship versus the pole coordinate shown in the printout (see Chapter II).
2. The plotting of the corrected righting arm curve and a determination of the residual heeling angle after damage in the equilibrium condition (i.e. when righting arm = 0).
3. The graphical determination from the righting arm curve of the residual $\overline{GM}$ at the equilibrium angle.
4. The plotting of draft and trim against heeling angles and the determination of final draft and trim at the equilibrium heeling angle.
5. The manual check of the final equilibrium waterline against the lines plan to determine minimum freeboard.

Obviously, the above calculations must be repeated for each damage condition.

Most organizations using SHCP have developed computer subroutines which can perform some or all of the above computations. In addition, subroutines have been developed using iterative techniques to determine the minimum $\overline{KG}$ for each condition required to meet the survival criteria.

Techniques vary among various subroutines. Some, for example, will determine the required $\overline{GM}$ by heeling the vessel one degree past the equilibrium angle and mathematically determining the slope between the righting arms at each angle. With the basic SHCP program, checks of the effects of intermediate flooding must also be done manually. Again, additional subroutines have been developed to perform this computation. While the effects of asymmetric flooding are accounted for in the basic SHCP program, any asymmetrical weight changes must be accounted for manually.

(c) Residual Range and Amplitude of Righting Arm. Where the survival criteria call for minimum range and amplitude of righting arms and minimum values of righting energy, i.e., areas under the righting arm curve, a plot of righting arms from the computer printout provides all the information required to determine compliance or noncompliance with the criterion, except for the location of any point of downflooding, which must be checked manually.

Many subroutines have been developed and are being used to plot the righting arm curve automatically, and to print out the point of downflooding and the amplitude of the maximum righting arm and the righting energy under the curve.

Other subroutines using iterative techniques have been developed to establish minimum $\overline{KG}$'s required to meet the survival criteria at various initial drafts.

Section 6
Definitions for Regulations

6.1 Introduction. The definitions given herein are for reference in connection with the regulations discussed in the following section. They are applicable to vessels complying with the traditional factorial and integer compartment length standards (Section 7) and are in agreement with (but not necessarily worded the same as those of) the U.S. Coast Guard Rules for Subdivision and Damaged Stability, and with the various International Conventions and IMO recommendations. Where differences among definitions applicable to specific classes of vessels occur, the differences are noted.

However, because the new IMO probability-based Equivalent Passenger Vessel Regulations (SOLAS Conference, 1974) contain a number of new and differing definitions, they have been separately set forth in Section 8.

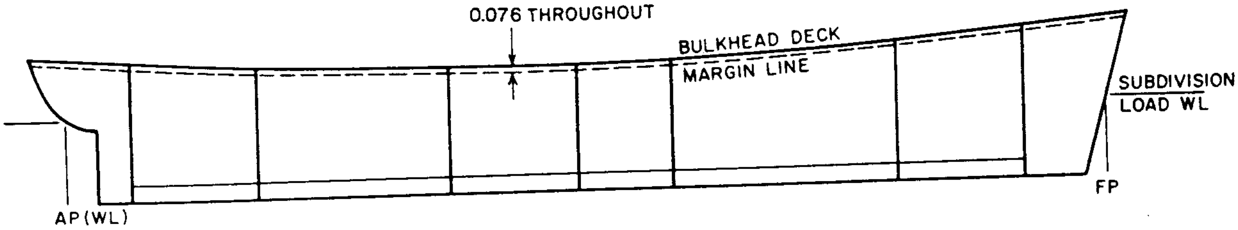
The U.S. regulations for bulk chemical and liquefied gas carriers contain a number of definitions for tanks, spaces, etc., peculiar to those classes of ship that are not included herein. The reader is referred to the Code of Federal Regulations (46 CFR 153 and 154).

Offshore mobile drilling unit require definitions for length, etc., differing widely from standard types of ships and are also not included. The reader is referred to the American Bureau of Shipping *Rules for Building and Classing Offshore Drilling Vessels.*

When the permissive subdivision regulations for tankers were included in the 1966 Load Line Convention, the IMCO delegates adopted the same definition of length that has always been used for load line provisions—essentially length between perpendiculars—rather than length on the subdivision waterline. This made it easier for the regulatory officer preparing a load line certificate, but caused some confusion among naval architects wondering whether to put the end stations for lines drawings and hydrostatic calculations at the ends of the subdivision waterline or at the perpendiculars. However, the procedure of setting the end stations at the waterline is commonly accepted, though some designers still use the length between perpendiculars and account for volumes beyond the perpendiculars by adding additional stations.

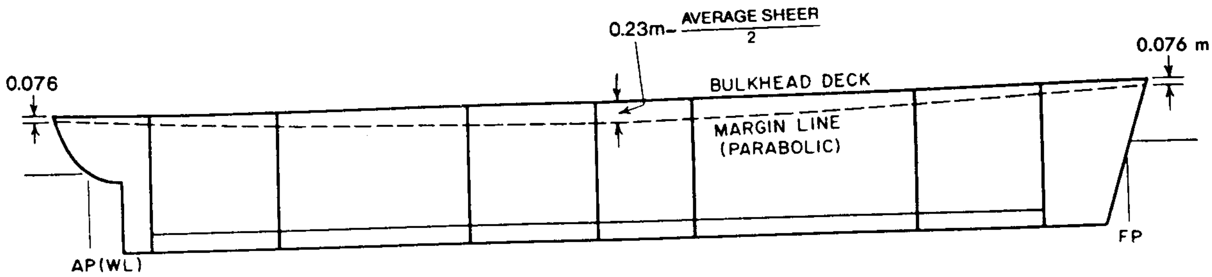
6.2 Definitions.

(a) Subdivision Load Line. The subdivision load line is the waterline used in determining the subdivision of the vessel. The deepest subdivision load line is the waterline which corresponds to the greatest draft permitted by the applicable subdivision requirements (including stability considerations). This may or may not be the same as the loadline assigned for freeboard or scantlings.



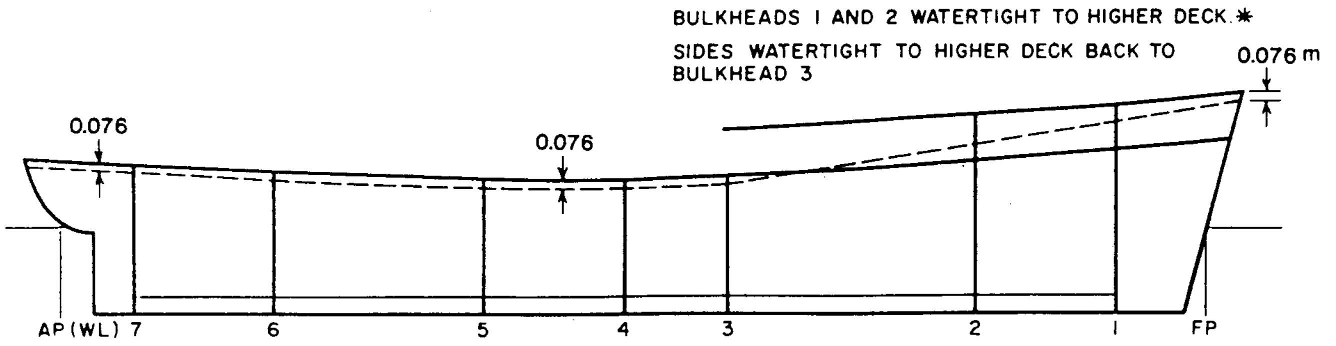
THE AVERAGE VALUE OF THE SHEER AT THE FP AND AP IS AT LEAST 0.30m (12 IN)

Fig. 34 Margin line with continuous bulkhead deck



THE AVERAGE VALUE OF THE SHEER AT THE FP AND THE AP IS LESS THAN 0.30m (12 IN) (U.S. COAST GUARD RULES)

Fig. 35 Margin line with continuous bulkhead deck



IN THE CASE SHOWN THE HIGHER DECK IS CONSIDERED THE BULKHEAD DECK AFT TO BULKHEAD 3

* IN BULKHEAD 2 LIMITED NON-WATERTIGHT PENETRATIONS MAY BE SPECIALLY PERMITTED IF INBOARD OF VERTICAL LINES LOCATED 1/4 B FROM THE CL AND IF:

(a) NOT LESS THAN 0.23m ABOVE THE MARGIN LINE
(b) NOT MORE THAN 0.6m BELOW THE MOLDED LINE OF THE BULKHEAD DECK

SUCH SPECIALLY APPROVED OPENINGS ARE REQUIRED TO BE INDICATED BY A PLAN CARRIED ABOARD THE SHIP

Fig. 36 Margin line where bulkhead deck is stepped

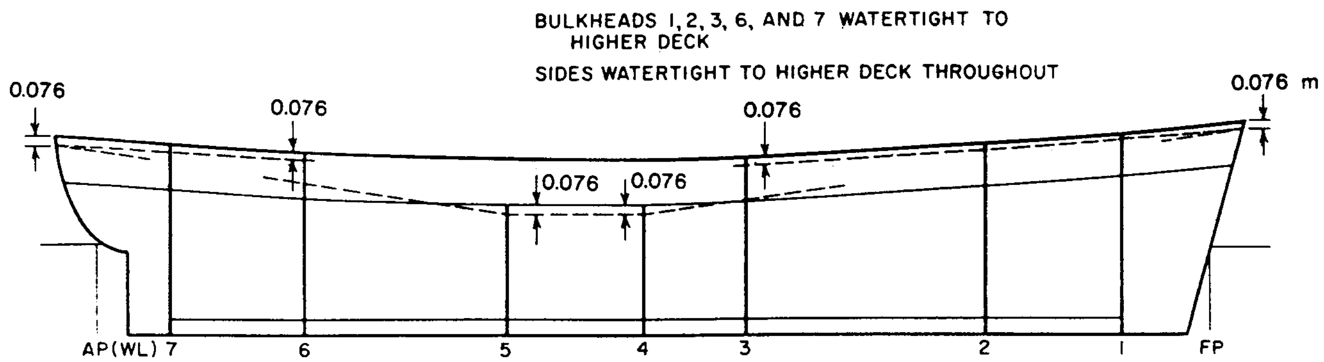


Fig. 37 Case where more than one margin line is required

(b) Subdivision Length.

1. *U.S. Passenger Vessels and Oceanographic Vessels*

The subdivision length is the length measured between perpendiculars at the extremities of the subdivision load line.

2. *Tankers, Bulk Chemical and Liquefied Gas Carriers, Large Fishing Vessels and Offshore Supply Vessels*

Length (L) is taken as 96 percent of the total length on a waterline at 85 percent of the least molded depth measured from the top of the keel, or as the length from the fore side of the stem to the axis of the rudder stock on that waterline, if that be greater. In vessels designed with a "rake of keel" (drag), the waterline on which this length is measured is taken as parallel to the designed waterline.

(c) Breadth of Vessel. The breadth of the vessel is the extreme molded width at or below the deepest subdivision load line. On wood vessels, breadth is taken to the outside of the planking.

(d) Bulkhead Deck. The bulkhead deck is the uppermost deck to which the transverse watertight bulkheads and the shell are carried.

(e) Margin Line. The concept of the margin line was adopted in the original 1929 Convention and has been continued for U.S. Passenger Vessels, oceanograhic vessel regulations, vessels under Maritime Administration jurisdiction, and subsequent international conventions on passenger vessels since that date. However, it is not used in the new equivalent regulations for passenger vessels or in the regulations for subdivision of other classes of ships. It is accepted in principle by the U.S. Navy.

The margin line is a line defining the highest permissible location on the side of the vessel of any damaged waterplane in the final condition of sinkage, trim and heel. It is in no case permitted to be less than 7.5 cm (3 in.) below the top of the bulkhead deck at the side. In certain cases the subdivision of one portion of the ship may relate to one margin line while the balance of the ship is calculated to another. The various ways in which margin lines are assigned are illustrated in Figs. 34 through 37.

(f) Draft. The draft is the vertical distance from the molded baseline amidships to the waterline in question. In case of floodable length calculations, as required by the traditional factorial standards, this waterline is always the subdivision load line. In the case of all other subdivision standards and all damage stability calculations, the waterline to which the draft is measured is the one at which the vessel is floating in the operating condition.

(g) Volume. In all cases volumes are calculated to molded lines. The volumes of flooded spaces are calculated only to the waterline after sinkage.

(h) Permeability. The volume permeability of a space is the percentage of the space that can be occupied by water. Surface permeability is the percentage of a waterplane that can be occupied by water.

(i) Intact Buoyancy. The term intact buoyancy is used to describe spaces within the limits of damaged compartments that are undamaged and not open to the sea.

(j) Machinery Space. The machinery space is taken as extending from the molded baseline to the margin line or deck line and between the extreme main transverse watertight bulkheads bounding the spaces devoted to the main and auxiliary propelling machinery, boilers serving the needs of propulsion and all permanent coal bunkers. In the case of unusual arrangements, special consideration may be necessary.

(k) Passenger Space. Passenger spaces are those provided for the accommodation and use of passengers, excluding baggage, stores, provision and mail rooms. For the purpose of permeability calculations, crew spaces and all other spaces which, in the fully-loaded condition, normally contain no substantial quantity of cargo, coal, oil fuel, baggage, stores, provisions, or mail are treated as passenger spaces.

(l) Floodable Length. The floodable length at any point in the length of the ship (as previously defined) is the maximum portion of the length, having its center at the point in question, that can be symmetrically flooded at the prescribed permeability, without immersing the margin line.

(m) Criterion of Service. The criterion of service is a numeral intended to express the degree to which a vessel is a passenger vessel. In principle, a numeral of 23 corresponds to a vessel engaged primarily in carrying cargo, with accommodations for a small number of passengers, while a numeral of 123 is intended to apply to a vessel engaged solely, or very nearly so, in the carriage of passengers. See Section 7.

(n) Factor of Subdivision. The factor of subdivision is a factor prescribed by the applicable regulations and by international convention (Section 7) that depends on ship length and criterion of service. See permissible length.

(o) Permissible Length. The permissible length at any point is obtained by multiplying the floodable length at that point by the factor of subdivision.

It should be noted that these paragraphs 12, 13, 14, and 15 contain definitions applicable only to the traditional factorial standards for passenger vessels. See Section 7.

(p) Use of Positive and Negative Signs. In addition to their conventional use to indicate addition or subtraction, these signs have the following special usages in this chapter:

	Plus (+)	Minus (−)
Longitudinal levers, trim, etc.	Forward	Aft
Transverse levers, heel, etc.	Starboard	Port
Vertical levers, shifts, etc.	Up or above	Down or below

(q) Large Fishing Vessel. A large fishing vessel is defined by IMO as a fish-catching vessel over 100m (300 ft) in length and carrying more than 100 persons on board.

(r) Administration. This term is used to indicate the governmental body responsible for administering the particular regulation under discussion.

Section 7
Subdivision and Damage Stability Criteria

7.1 General. All subdivision and damage stability criteria or regulations must provide the answers to the following three key questions:

(a) What is the extent of damage to which the ship is assumed to be subjected?

(b) Where is the damage assumed to be located? Primarily, can it occur between bulkheads, or on one or more specific bulkheads, or on any bulkhead?

(c) What condition is the ship permitted to be in after the assumed damage? What is the permissible sinkage, trim and heel; the residual $\overline{GM}$ and/or $\overline{GZ}$, righting energy and range of stability; and what limits

are placed on the location of the waterline in a flooded condition? Or what is the required initial stability?

In addition, all criteria set forth special requirements for such items as assumed permeabilities, minimum bulkhead spacing, local subdivision and equalization after flooding.

Since their inception, criteria for subdivision and damage stability of passenger ships have dealt only with side or end damage. This practice has been followed in the Maritime Administration criteria and in the criteria for large fishing vessels, offshore supply vessels and mobile drilling units. This was undoubtedly due to the belief of the authorities that the requirements for double bottoms in the SOLAS conventions, and their use in general practice, provided adequate bottom protection against flooding. In the case of tankers, bulk chemical carriers and liquefied gas carriers, however, the authorities were concerned about the effect on the environment of escaping cargo and the need for added provisions regarding the extent of bottom damage. There are no requirements in subdivision or damage stability regulations for a ship to comply with any wind heel criterion after damage. However, the U.S. Navy does attempt to allow for the effect of wind on damage stability (section 7.5,(j).

At the time when international standards were being developed, combination cargo and passenger vessels made up the great majority of the world's fleet carrying passengers on international voyages. It was this type of ship that dictated the standards for passenger vessels. Their use has declined steadily and now those remaining are primarily in the pilgrim trade or in out-of-the-way services. The influence of combination cargo and passenger vessels still remains, however, and will continue until they disappear.

After a great deal of preliminary discussion of criteria for subdivision, the 1929 International Conference on Safety of Life at Sea accepted the concept that there is a continuously increasing safety with decreasing bulkhead spacing. Hence, instead of prescribing one, two and three-compartment subdivision, with the bulkhead spacing as long as possible within each grade of subdivision, the Convention gave a permissible length that is obtained by multiplying the floodable length by a factor less than (or, as a limit, equal to) unity, called the factor of subdivision. By this factorial system a factor of subdivision of 1.0 corresponds to a one-compartment standard (i.e., any one compartment can be flooded without the ship sinking—under assumed conditions), 0.5 to a two-compartment standard, etc. An intermediate factor such as 0.75, for example, would correspond to a one-compartment standard under rule assumptions regarding drafts before damage, permeabilities, etc., but it was assumed that under certain more favorable conditions the ship might survive with two compartments flooded (i.e., side damage at a bulkhead.) Hence, the doubtful presumption that a ship with factor of subdivision of 0.75 is safer than one with a factor of 1.0.

As noted in Section 1, an entirely different probabilistic approach to subdivision was introduced at the 1974 SOLAS Conference, and the resulting Alternate Equivalent Passenger Regulations were included in the 1974 Convention. See Section 8. The basic philosophy now is that the true index of safety is the probability of survival after damage occurring anywhere along the length of the ship, between or on a bulkhead.

Under the factorial standards to be summarized in this section, it will be found that a vessel around 180m (600 ft) in length and carrying only six hundred passengers and no cargo is not required to meet a two-compartment standard. Passenger vessels on international voyages in the past twenty years have been constructed either as cruise ships, or as combination automobile and passenger ferries. For both types of ship there is no economic need for large cargo holds. The spaces below the freeboard deck can be subdivided with ample bulkheads to permit them to meet a two-compartment standard without penalizing them unduly. A vessel carrying passengers below the freeboard deck may require a few more bulkheads, a few more sliding watertight doors and a few more stairways, but the costs of these are insignificant in relation to the total cost and relative safety of the ships. Automobile and passenger ferries may easily meet a two-compartment standard with car decks extending below the freeboard deck. See Robertson, et al (1974).

The naval architect should feel a great deal more comfortable if one's passenger ship can sustain damage anywhere in the vessel's length, i.e. meets a two-compartment standard, without the need to worry about the probability of damage occurring at a bulkhead. Such a standard has been easily met on United States inland and coastwise vessels over 100m in length, and it is desirable for it to be met on similar ocean going passenger vessels wherever possible.

On ships travelling on international routes, coming under the jurisdiction of the SOLAS Conventions, any ship carrying more than 12 passengers is classed as a passenger vessel. Ships operating on voyages between any two American ports, which are covered under the U.S. Coast Guard regulations, are classed as passenger vessels if they carry more than 16 persons. Small U.S. passenger vessels, again operating between U.S. ports and which come under SubChapter "T" Regulations, are classed as passenger vessels if they carry more than 6 passengers.

7.2 Summary of U.S. and International Standards. Standards for subdivision and damage stability have been established by International Conventions, by recommendations of IMO, by national regulations and by classification society rules. These standards can be subdivided into two types. The first type uses the traditional *factorial* system. The second type uses the *integer compartmentation* system. In the latter, the standards require the ship to survive damage to 1, 2 or more compartments, in parts or in all of the ship.

In the following summary, under the several standards, the types of ships to which the standards are applicable are listed giving the U.S. (Coast Guard) regulations (if any), the International Convention or IMO recommendation (if any), and the classification society rules (if any), applicable to each type.

(a) Traditional factorial system standards are applicable to all passenger vessels on international voyages, and U.S. passenger vessels over 150 gross tons on domestic ocean and coastwise voyages.

International Standards:	SOLAS Conventions, 1929, 1948, 1960, 1974
U.S. Regulations:	U.S. Code of Federal Regulations: 46 CFR 73.10, 74.10-15

(b) Alternate equivalent passenger vessel standards are also applicable to all passenger vessels on international voyages, and U.S. passenger vessels over 150 gross tons on domestic ocean and coastwise voyages. Note that these are alternate standards which are recommended by IMO and accepted by U.S. and other governments as equivalent to the traditional factorial system standards. See Section 8.

(c) Integer Compartmentation Standards are applicable to various types of ships in accordance with Table 2.

It should be understood that, where U.S. regulations are listed, these are the law of the land and must be compiled with on U.S. vessels of the type described. Foreign countries, however, will permit such vessels in their waters only when they comply with the requirements of International Conventions which have been ratified and are in force. All U.S. regulations are equal to, or exceed the requirements of ratified International Conventions. Where IMO resolutions are listed as the International Standards, these are recommendations only and are not legally binding on vessels in international trade. The only case where an International Convention is listed and the United States has no regulations is the Convention on fishing vessels, and this convention has not, at this date, been ratified by a sufficient number of countries to bring it into force.

IMO is working continually toward the goal of uniformity in international standards and consequently various "harmonization proposals" have been made from time to time. Some of these are noted in Section 7.3.

Detailed requirements for the different classes of ships listed in Table 2 are presented in the following sections under these headings:

7.3 Extent of damage
7.4 Damage location
7.5 Damage survival
7.6 Special requirements

The American Bureau of Shipping special requirements for mobile offshore drilling vessels, whether they are self-elevating, column stabilizing, or surface drilling units, are too complex to detail here. The Bureau also has a computer program for analyzing the damage stability of the various types of drilling units.

Table 2—Integer Compartment Standards Applicable to Different Types of Ships

	International Standards	U.S. Regulations
U.S. passenger vessels, in other than ocean and coastwise service	None	46CFR 73.15 & 74.10-15
U.S. passenger vessels under 150 GT, on a domestic ocean or coastwise voyage	None	46CFR 73.15 & 74.10-15
Small U.S. passenger vessels (under 100 GT) not on an international voyage	None	46CFR 178
Oceanographic ships	None	46CFR 191
Dry cargo ships (including dry bulk carriers, roll-on-roll-off ships)	None	USCG* U.S. Vessels under MARAD jurisdiction: Des.Letter No. 3A
Tankers	MARPOL'73	46CFR 42 33CFR 157
Bulk chemical carriers	IMO Res. No. 212	46CFR 153
Liquefied gas carriers	IMO Res. No. 328	46CFR 154
Offshore supply vessels	IMO Res. No. A469 (XII)	None
Large fishing vessels	Int. Conf. on Fishing Ves. '77	None
Mobile offshore drilling vessels	IMO Res. No. A414 (XI)	ABS Rules for Bldg. & Classing Mob.Drilling Ves. 46CFR 107-109
Naval vessels	None	Naval Sea Sys. Com., Des. Data Sheet,DDS 079-1

* No regulations, except that U.S. cargo vessels complying with special requirements for hatch covers and other areas through which water could enter the hull, *may* obtain a reduction in freeboard by complying with certain subdivision requirements. See 46CFR 42. These special requirements are readily and therefore commonly adopted in dry bulk carriers.

7.3 Extent of Damage. *(a) General.* While not specifically spelled out in all regulations, it is generally required and commonly accepted that if a lesser extent of damage than those specified in the regulations result in a more severe condition regarding heel or loss of metacentric height, then such lesser extent should be assumed. One example of the need for such a requirement is a vessel with high side tanks with inboard longitudinal bulkheads spaced less than $B/5$ from the shell. Flooding such tanks alone when empty could cause a greater heel than that caused by flooding both the side tank and inboard compartment.

In all cases, the transverse extent of damage is measured from the waterline at the point of minimum beam in way of damage.

In the early passenger vessel regulations, the longitudinal extent of damage was expressed as a fixed amount 3.05m (10 ft), plus a percentage (3.0) of the length. Later regulations adopted a fixed percentage of a power of the length, i.e.: $1/3L^{2/3}$ or $0.495L^{2/3}$ ft. or a fixed length, whichever is the least. A comparison of the values obtained by each of these formulas is given in Table 3, for a representative list of ship lengths.

Table 3—Longitudinal Extent of Damage

Length of Ship		$.03L + 3.05$m		$1/3L^{2/3}$ (L in m)	
m	ft	m	ft	m	ft
30.49	100	3.96	13.0	3.26	10.7
60.98	200	4.88	16.0	5.15	16.9
91.46	300	5.79	19.0	6.79	22.3
121.95	400	6.71	22.0	8.20	26.0
152.44	500	7.62	25.0	9.51	31.2
182.93	600	8.54	28.0	10.73	35.2
213.41	700	9.45	31.0	11.92	39.1
243.90	800	10.37	34.0	12.99	42.6

The U.S. regulations on extent of damage for tankers stem from the 1973 Pollution Convention. Bulk chemical ships and liquefied gas carriers stem from IMO Codes. The difference in extent of damage between the two regulations is minor. IMO is now in the process of "harmonizing" these recommendations and it is expected that the U.S. will follow its lead. Notes have been appended to the stated requirements for these vessels in Section 7.3, showing the status of the IMO proposals at the time of writing. Again, the reader is cautioned to check the latest U.S. regulations on any new design.

(b) U.S. Passenger Vessel Regulations. The required assumed extent of side damage in United States passenger vessels on an international voyage, or over 150 gross tons in ocean or coastwise service (assumed to be rectangular both in plan and elevation) is given by Table 4.

The transverse extent of damage (penetration) is measured inboard of the vessel's side and at right angles to the centerline at the level of the deepest subdivision load line. In the United States rules, for vessels on inland waters and for ferry vessels, where the maximum molded beam at the deck and at the load waterline differ appreciably, the transverse extent of damage throughout the ship is taken as the mean between the inboard penetration of the deck, using the maximum beam at the deck, and the inboard penetration at the deepest subdivision load line, using the maximum beam at the load line.

For passenger vessels under 100 gross tons, the Coast Guard has special requirements dependent on length and number of passengers. The reader is referred to the detail regulations in 46 CFR 178 for these requirements.

(c) Oceanographic Vessels. It is assumed that the longitudinal extent of damage does not exceed 3.05m

Table 4—Assumed Extent of Damage

Vessel Category	Longitudinal Extent	Transverse Extent	Vertical Extent
All vessels	3.05m (10 ft) + $0.03L$ or 10.7m (35 ft) whichever is less—no main bulkhead involved	$B/5$	From baseline upward without limit
Vessels without factor of subdivision, where a two-compartment standard is required	3.05m (10 ft) + $0.03L$ or 10.7m (35 ft) whichever is less, involving one main bulkhead	$B/5$	From baseline upward without limit
Vessels with a factor of subdivision of 0.50 or less	3.05m (10 ft) + $0.03L$) or 10.7m (35 ft) whichever is less, involving one main bulkhead	$B/5$	From baseline upward without limit
Vessels with a factor of subdivision of 0.50 or less	6.1m (20 ft) + $0.04L$ involving not more than one main bulkhead[a]	$B/5$	Top of double bottom to margin line[b]
Vessels with a factor of subdivision of 0.33 or less	6.1m (20 ft) + $0.04L$ but in any case long enough to involve two main bulkheads[a]	$B/5$	From baseline upward without limit

[a] 3.05m (10 ft) plus $0.03L$ in the 1974 International Convention.
[b] From the baseline in the 1974 International Convention.

(10 ft) plus $0.03L$. Transverse or vertical extent of damage is not defined.

(d) Cargo Ships. The Maritime Administration assumes, on all major vessels built under government subsidy or mortgage insurance programs, that damage occurs on the side and does not extend to main transverse bulkheads unless they are spaced closer than the required length of damage which is $0.495L^{2/3}$ or 14.5m (47.6 ft), whichever is less. Where U.S. Coast Guard regulations for specific ship types impose more severe requirements, these supersede the Maritime Administration standard. The assumed transverse extent of damage is $B/5$ and the vertical extent is unlimited above and below the baseline.

(e) Tankers (U.S. Regulations). For side damage, the extent of damage assumed is:

• Longitudinal extent	$1/3L^{2/3}$ or 14.5 meters (47.5 ft) whichever is less
• Transverse extent (inboard from the vessel's side at the level corresponding to the assigned summer freeboard)	B/5 or 11.5 meters (37.7 ft) whichever is less
• Vertical extent	From the baseline upward without limit

For bottom damage, the extent of damage assumed is:

Damage	From 0.3L from the forward perpendicular of the ship	Any other part of the ship
• Longitudinal extent	$L/10$ (See Note 1)	$L/10$ or 5 meters, whichever is less. (See Note 2)
• Transverse extent	$B/6$ or 10 meters whichever is less, but not less than 5 meters	5 meters (See Note 3)
• Vertical extent from the baseline	$B/15$ or 6 meters, whichever is less	$B/15$ or 6 meters, whichever is less

Note 1: The IMO harmonization proposal would change this to $1/3L^{2/3}$ or 14.5 meters, whichever is less.
Note 2: The IMO harmonization proposal would change this to $1/3L^{2/3}$ or 5 meters, whichever is less.
Note 3: The IMO harmonization proposal would change this to $B/6$ or 5 meters, whichever is less

(f) Bulk Chemical Carriers (U.S. Regulations). It is assumed that damage can occur from either collision or grounding damage, and the damage must consist of the most disabling penetration up to and including penetrations having the following dimensions:

(1) *Collision penetration:*

• Longitudinal extent	$(1/3)L^{2/3}$ or 14.5m (approx. $0.495L^{2/3}$ or 47.6 ft), whichever is less.
• Transverse extent: (inboard from the ship's side at right angles to the centerline at the level of the summer load line assigned)	$B/5$ or 11.5m (approx. 37.7 ft), whichever is less
• Vertical extent	From the base line upwards without limits.

(2) *Grounding penetration:*

Damage	At forward end, but excluding damage aft of point 0.3L aft of FPP	At any other longitudinal position
• Longitudinal See Note 1	$L/10$	$L/10$ or 5m (approx. 16.4 ft), whichever is less. See Note 1.
• Transverse See Note 2.	$B/6$ or 10m (approx. 32.8 ft), whichever is less.	5m (approx. 16.4 ft)
• Vertical extent from the base line.	$B/15$ or 6m (approx. 19.7 ft), whichever is less.	$B/15$ or 6m (approx. 19.7 ft), whichever is less

Note 1: The IMO harmonization proposal would change the longitudinal extent of damage in locations forward of the $0.03L$ to $1/3L^{2/3}$ or 14.5m whichever is less. In other longitudinal locations it is $1/3L^{2/3}$ or 5 meters, whichever is less.
Note 2: IMO harmonization proposal would change the transverse extent in "other longitudinal positions" to $\frac{B}{6}$ or 5m, whichever is less.

If the damage assumption excludes a transverse bulkhead bounding a machinery space, the machinery space must be assumed to be flooded as a case separate from the damage assumption.

(g) Liquefied Gas Carriers (U.S. Regulations).

(1) For side damage, the extent of damage assumed is:

• Longitudinal extent	$1/3L^{2/3}$ or 14.5m, whichever is less.
• Transverse extent (inboard from the ship's side at right angles to the centerline of the level of the summer load line)	$B/5$ or 11.5m, whichever is less
• Vertical extent	From the baseline upward without limit.

(2) Bottom damage:

Damage	At forward end, but not including damage aft of point 0.3L aft of FPP	At any other longitudinal location
• Longitudinal extent	$1/3L^{2/3}$ or 14.5m, whichever is less	$L/10$ or 5m whichever is less (See Note 1)
• Transverse	$B/6$ or 10m, whichever is less	$B/6$ or 5m, whichever is less
• Vertical extent from the molded line of the shell at the centerline	$B/16$ or 2m, whichever is less	$B/16$ or 2m, whichever is less

Note 1: the IMO harmonization proposal would change this to $1/3L^{2/3}$ or 5m, whichever is less.

(h) Offshore Supply Vessels (IMO Recommendations)

The assumed extent of damage is as follows:

• Longitudinal extent	No provision
• Transverse extent	760mm (30 in.)
• Vertical extent	Full depth of ship

(i) Large Fishing Vessels (IMO Recommendations).
The assumed extent of damage is as follows:

• Longitudinal extent	$1/3L^{2/3}$m (0.495 $L^{2/3}$ in ft)
• Transverse extent (inboard from the side at right angles to centerline at level of deepest operating WL)	$B/5$
• Vertical extent	From the baseline upward without limit

(j) U.S. Naval Vessels.
The extent of damage assumed on U.S. naval vessels depends on the ship type and the ship size. On large combatant vessels with side protection systems such as aircraft carriers, the extent of damage is classified and is based on test data, war damage reports and design experience.

New designs without side protection systems under 91.5m (300 ft) in length are not required to meet a specified longitudinal extent of damage. New designs for vessels over 91.5m (300 ft) are required to withstand flooding from damage equal to 15 percent of the vessel's length if it is a combatant type or personnel carrier. All other types of vessels this size must withstand flooding from damage equal to 12.5 percent of the vessel's length.

The transverse extent of damage for all ships without side protective systems is one-half the beam, but not including a centerline bulkhead. The vertical extent of damage is from the keel upward, except that if *not* flooding the inner bottom results in a worse condition, this is assumed.

Special criteria are assigned to merchant vessels converted to naval auxiliaries, depending on the ship type. If primarily designed for the carriage of cargo, they must meet a two-compartment standard. Other vessels must withstand flooding from an opening in the shell of 12.5 percent of the ship's length.

7.4 Location of Damage.

(a) General. In all criteria the damage is assumed to take place anywhere within the ship's length. However, where all or portions of the ship are only required to meet a one-compartment standard of subdivision, the damage is assumed to take place between watertight transverse bulkheads that are a distance apart equal to or greater than the assumed longitudinal extent of damage. Where a two-compartment standard of subdivision is required by the criterion the damage is assumed to be located anywhere throughout the ship's length, or throughout the specified portion of the ship, including damage at any one of the main transverse watertight bulkheads within these areas. Where three-compartment damage is required, the damaged is presumed to be located so as to include two adjacent main watertight bulkheads.

(b) U.S. Passenger Vessel Regulations (Coast Guard). If the factor of subdivision is above the value of 0.5, the vessel must meet a one-compartment standard and the location of damage is therefore anywhere in the vessel's length, but not including a bulkhead. If the ship must meet a two, three or four-compartment standard, again the damage is assumed to occur anywhere in the ship's length, but to include damage to any one bulkhead or to any two or three adjacent bulkheads, respectively.

For U.S. Passenger Vessels in Service Other than Ocean or Coastwise, or Under 150 Gross Tons in Ocean or Coastwise Service, but not on an International Voyage, the factorial system of subdivision is not used; see 46 CFR 73.15. Instead, for passenger vessels other than automobile ferries, the requirements call for compliance with either a one-compartment or a two-compartment standard of flooding, including stability, depending upon the number of passengers. All passenger vessels must meet a one-compartment standard throughout their length. Vessels carrying more than 400 passengers must not submerge the margin line with the forepeak and one adjacent compartment flooded; vessels carrying more than 600 passengers are required to meet a two-compartment standard forward within at least a full 40 percent of their length; vessels carrying more than 800 passengers forward within at least a full 60 percent of their length; and vessels carrying more than 1000 passengers are required to meet a two-compartment standard throughout their length.

All ferry vessels under 46m (150 ft) in length must meet a one-compartment standard; all vessels over 46m (150 ft) in length must meet a one-compartment standard and additionally be able to withstand flooding of the peak compartment and one adjacent compartment; and all ferry vessels over 61m (200 ft) in length must meet a two-compartment standard.

(c) Oceanographic Ships and Dry Cargo Ships. Damage can occur anywhere in the vessel's length, but is assumed to occur between main transverse bulkheads.

(d) Tankers. The location of damage in tankers over 225 meters (782 ft) in length is anywhere in the vessel's length. Thus, the vessel has to meet at least a two-compartment subdivision standard.

For tankers between 150 meters (492 ft), but not exceeding 225 meters (738 ft) in length, the damage location is anywhere in the vessel's length outside of the machinery space. It is assumed not to occur on either the forward or after machinery space bulkhead. Therefore, the machinery space compartment has to meet only a one-compartment standard of subdivision, but all of the other spaces have to meet a two-compartment standard. For tankers not exceeding 150 meters (492 ft) in length, damage is assumed to occur anywhere in the ship's length between adjacent transverse bulkheads with the exception of the machinery space. Thus the vessel has to meet the one-compartment standard in compartments outside of the machinery space, but does not have to survive damage occurring between the machinery space bulkheads.

Since the Maritime Administration requires a one-compartment standard on all vessels under its jurisdiction, its requirements exceed the U.S. Coast Guard on tankers under 150 meters (492 ft) in length in that the machinery space must be capable of being flooded.

(e) Bulk Chemical Carriers and Liquefied Natural Gas Carriers. Vessels in these categories are broken down into sub-classes, based on the severity of the hazard to the crew and to the environment if a compartment is flooded. The damage assumptions for each class vary widely from minimum location between transverse bulkheads to locations at single or multiple combinations of bulkheads. The reader is advised to check the detailed regulations applying to the particular class of ship for the exact requirements for that particular class.

(f) Large Fishing Vessels and Offshore Supply Vessels. Damage is assumed to occur anywhere in the vessel's length, but only between transverse bulkheads.

(g) Naval Vessels. On vessels with side protective systems the damage is assumed to occur at any place in the ship's length. Other vessels under 30.5m (100 ft) in length must withstand damage anywhere between watertight bulkheads or meet a one-compartment standard. Other vessels between 30.5m (100 ft) and 91.5m (300 ft) in length must withstand damage anywhere in the ship's hull, including one watertight bulkhead or meet a two-compartment standard.

Vessels over 91.5m (300 ft) must withstand damage of the extent given in 7.3 (10), anywhere in the vessel's length.

7.5 Damage Survival.

(a) Operating Drafts. The calculations for floodable length under the traditional passenger vessel regulations are performed at the subdivision draft only. This is logical because the effect of sinkage and trim, and the probability of submerging the margin line due to sinkage and trim, is much greater in the fully loaded condition. In calculating damaged stability, however, the benefits of increased freeboard at light draft can be offset by changes in $\overline{KG}$ in the various operating conditions. Therefore, to insure that the worst operating condition is covered, all other criteria call for the vessel to meet the damage survival requirement at the full range of operating drafts and trims. The detailed regulations for each case should be checked for the conditions specified.

(b) U.S. Passenger Ship Regulations. After damage, the vessel must meet the following survival conditions:

1. *Margin Line.* In the final flooded condition, the margin line must not be submerged at any place in the ship's length.

2. *Metacentric height.* In the final flooded condition there should be a positive residual metacentric height of at least 0.05 m (2 in.).

3. *Heel must not exceed specified limits.* The present regulations concerning limits of permissible heel deliberately incorporate some flexibility. Consideration of the factors affecting the relationship of heel to risk provides some guidance as to their application and explains why they leave, in some cases, latitude for administrative interpretation. The considerations involved in dealing with heel may be grouped as follows:

- The effect of heel on the safe movement and control of persons on board the vessel, on the risk of shifting of weights, and on the ability to launch lifeboats;
- The risk relative to flooding through side or deck openings;
- The relationship of heel to the range of stability and the angle and value of the maximum righting arm;
- The degree of accuracy with which the heel can be estimated.

It can be seen that consideration of heel is a complex matter, involving at this stage of knowledge, some exercise of judgment within the limits prescribed by the Rules, which are as follows:

For unsymmetrical flooding with assumed side damage not more than 3m (10 ft) plus $0.03L$, the remaining heel due to unsymmetrical moment, after equalization, shall not exceed 7 deg. However, where equalization is fully automatic and by open cross connections of large area, or where no equalization is involved, and in any case, the range of stability in the damaged condition is considered adequate, a greater heel up to but not in excess of 15 deg may be allowed. (The first part of this regulation refers basically to the case where a part of the unsymmetrical flooding is equalized through manually operated cross connections. In such case, the risk of delay or improper operation of these connections is the basis for the 7-deg limit. The relaxation permitted by the second part of the regulation is on the basis that there is no risk of malfunction of cross-connections and is on the further basis that damaged-condition range of stability and maximum righting arm are sufficient for the greater heel.)

Where the assumed side damage is more than 3m (10 ft) plus $0.03L$, the final heel due to unsymmetrical moment, after equalization, may be 15 deg, unless an insufficiency of righting arms would be cause for limiting the heel to a lesser value.

4. *Residual Righting Arm.* While a range of residual righting arm is not specified in these regulations, the regulations state that the range should be examined and the cognizant administration satisfied that they are adequate. This was traditionally done by approximate methods. At the present time an accurately calculated residual righting arm is generally required.

(c) Oceanographic Ships. Damage to any one compartment must not submerge the margin line.

(d) Cargo Ships. For ships under its jurisdiction the Maritime Administration requires, after damage, the following survival conditions:

1. The equilibrium heel angle θ_1 must be less than 15 deg.

2. Downflooding points must not be submerged at θ_1, unless fitted with watertight closing appliances, which then must remain shut at sea and be so logged.

3. The margin line must not be submerged at θ_1 unless it can be clearly shown that downflooding will not occur.

4. There must be a range of positive stability of at least 20 deg beyond the equilibrium heel angle and no downflooding openings may be within this 20 deg range unless they are fitted with watertight closing appliances.

5. The maximum residual righting arm, within the 20 deg range, must be last least 0.1m (4 in.).

6. For cases of symmetrical damage, the vessel must have 0.05 meters (2 in.) of positive $\overline{GM}$ in the upright condition after damage.

(e) Tankers (MARPOL, 1973). Oil tankers shall be regarded as complying with the criteria if the following survival requirements are met:

1. *The final waterline,* taking into account sinkage, heel and trim, shall be below the lower edge of any opening through which progressive flooding may take place. Such openings shall include air pipes and those which are closed by means of weathertight doors or hatch covers and may exclude those openings closed by means of watertight manhole covers and flush scuttles, small watertight cargo tank hatch covers which maintain the high integrity of the deck, remotely operated watertight sliding doors, and side scuttles of the non-opening type.

2. *The angle of heel* due to unsymmetrical flooding shall not exceed 25 deg in the final stage of flooding, provided that this angle may be increased up to 30 deg if no deck edge immersion occurs.

3. *The righting lever curve* for acceptable stability in the final stage of flooding must have a range of at least 20 deg beyond the position of equilibrium in association with a maximum residual righting lever of at least 0.1 m (4 in.). For the calculations required in this section, weathertight openings or openings fitted with automatic closures (e.g. a pressure, vacuum relief valve or a vent fitted with a ball-check valve), need not be considered as points of downflooding within the range of residual stability, but other openings must be included in the calculations.

(f) Bulk Chemical Carriers. A bulk chemical carrier is presumed to survive, if it meets the following conditions:

1. *Heel Angle.* Except as indicated below, in the final condition of flooding the angle of heel must not exceed 15 deg (17 deg if no part of the freeboard deck is immersed).

The cognizant Administration should consider on a case-by-case basis vessels 150 m or less in length having heel angles greater than 17 deg, but less than 25 deg.

2. *Final Waterline.* The final waterline, taking into account sinkage, heel, and trim, must be below the lower edge of openings such as air pipes and openings closed by weathertight doors or hatch covers. The following types of openings may be submerged when the tankship is at the final waterline:

- Openings covered by watertight manhole covers or watertight flush scuttles.
- Small watertight cargo tank hatch covers.
- Remotely operated watertight sliding doors.
- Side scuttles of the non-opening type.

3. *Range of Stability.* Through an angle of 20 deg beyond its position of equilibrium after flooding, a tankship must meet the following conditions:

- The righting lever curve must be positive.
- The maximum of the righting lever curve must be at least 10 cm (approx. 4 in.).
- Each submerged opening must be weathertight.

4. *Metacentric Height.* After flooding, the tankship's metacentric height must be at least 5cm (approx. 2 in.) when the ship is in the upright position.

(g) Liquefied Natural Gas Carriers. A vessel is presumed to survive assumed damage if it meets the following conditions in the final stage of flooding:

1. *Heel Angle.* The maximum angle of heel must not exceed 30 deg.

2. *Final Waterline.* The waterline, taking into account sinkage, heel and trim, must be below the lower edge of openings such as air pipes and openings closed by weathertight doors or hatch covers, except openings closed by means of watertight manhole covers and watertight flush scuttles, small watertight cargo tank hatch covers that maintain the high integrity of the deck, remotely operated watertight sliding doors, and side scuttles of the non-opening type.

3. *Range of Stability.*

- The righting lever curve must be positive and have a minimum range of 20 deg beyond the angle of equilibrium.
- The maximum righting lever within the above range must be at least 100 mm (4 in.).
- Each opening within the 20 deg range beyond the angle of equilibrium must be at least weathertight.

4. *Metacentric Height.* After flooding the vessel's metacentric height must be at least 50 mm (2 in.) when the vessel is in the upright position.

(h) Offshore Supply Vessels must meet the following survival requirements:

1. *The final waterline,* taking into account sinkage, heel and trim, should be below the lower edge of any opening through which progressive flooding may take place. Such openings include air pipes and those which are capable of being closed by means of weathertight doors or hatch covers and may exclude those openings closed by means of watertight manhole covers and flush scuttles, small watertight cargo tank hatch covers which maintain the high integrity of the deck, remotely operated watertight sliding doors, and side scuttles of the non-opening type.

2. *The angle of heel* due to unsymmetrical flooding

should not exceed 15 deg in the final stage of flooding. This angle may be increased up to 17 deg if no deck immersion occurs.

3. *The stability* in the final stage of flooding should be investigated and may be regarded as sufficient if the righting lever curve has at least a range of 20 deg beyond the position of equilibrium in association with a maximum residual righting lever of at least 0.1 m (4 in.) within this range. Unprotected openings should not become immersed at an angle of heel within the prescribed minimum range of residual stability unless the space in question has been included as a floodable space in calculations for damage stability. Within this range, immersion of all the openings listed in (*a*) need not be considered as downflooding points providing air pipes are fitted with ball-check valves.

(*i*) *Large Fishing Vessels.* The vessel is considered to survive the conditions of damage provided the vessel remains afloat in a condition of stable equilibrium and satisfies the following stability criteria:

1. *The stability* in the final condition of flooding may be regarded as sufficient if the righting lever curve has a minimum range of 20 deg beyond the position of equilibrium in association with a residual righting lever of at least 0.1 m (4 in.). The area under the righting lever curve within this range should be not less than 0.0175 meter-radians (3.25 deg-ft). Consideration should be given to the potential hazard presented by protected or unprotected openings which may become temporarily immersed within the range of residual stability. The unflooded volume of the poop superstructure around the machinery space casing, provided the machinery casing is watertight at this level, may be taken into consideration in which the case the damage waterline should not be above the after end of the top of the poop superstructure deck at the centerline.

2. *The angle of heel* in the final condition of flooding should not exceed 20 deg.

3. *The initial metacentric height* of the damaged vessel in the final condition of flooding for the upright position should be positive and not less than 5 cm (2 in.).

(*j*) *U.S. Naval Vessels.* On vessels with side protective systems the emphasis of damage survival is to maintain the vessel after damage at a static heel (at GZ = 0) not to exceed 15 deg, which is the limiting angle at which all machinery and equipment is designed to operate, with a 20 deg list the maximum, since it is assumed that a vessel with such a list can be safely towed back to port. Naval design and operational procedures also require that arrangements be provided for rapidly correcting list to less than 5° by counterflooding from the sea, assuming that pumping equipment is operational.

On all vessels the degree of list or trim after damage must be such that the margin line (7.5 cm, or 3-in. below the bulkhead deck) is not submerged. This, as in all criteria, assumes a level, calm sea. The Navy, in addition, has certain minimum criteria for survival under specified wind and wave forces, which may involve submerging the margin line.

The stability after damage is considered adequate if the areas A_1 and A_2 on Fig. 38 have the relationship $A_1/A_2 \geq 1.4$. The point ϕ is the angle of down flooding or 45 deg whichever is less. Point C is the initial static angle of heel after damage.

The angle ϕ_r is the expected roll angle due to wind and waves. The righting arm curve is reduced by an amount equal to 0.05 cosine ϕ to account for unknown unsymmetrical flooding or transverse shift of loose material. Values of the constant for calculating the wind heel curve and the amplitude of the rolling angle ϕ_r are given in DDS-079-1. (See Chapter II).

(*k*) *Residual $\overline{GM}$ and Residual Righting Arms.* It will be noted that the passenger vessel criteria, including those in the alternate equivalent regulations, call for a minimum residual $\overline{GM}$ for survival after damage. All other international criteria—such as the International Regulations recently adopted for tankers, bulk chemical carriers, liquefied natural gas car-

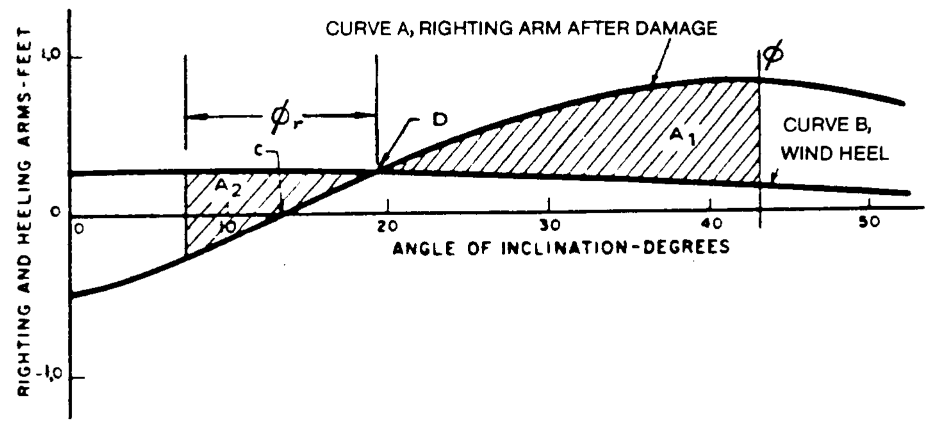


Fig. 38 U.S. Navy standard for stability after damage

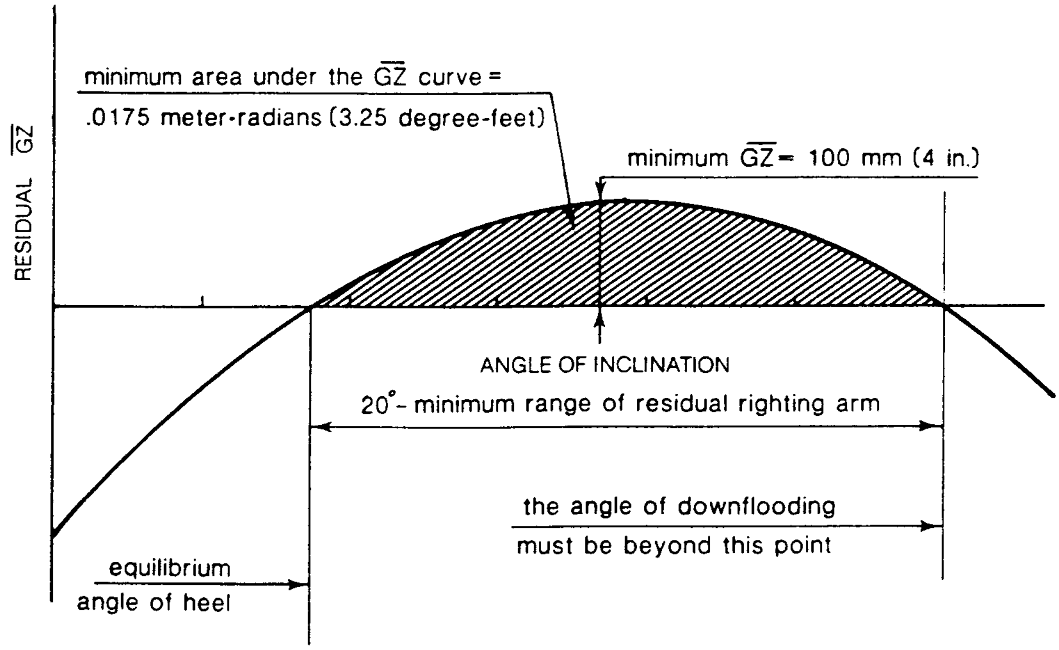


Fig. 39 Typical standards for required residual righting arms

riers, offshore supply vessels and large fishing vessels—specify minimum amplitude and range of righting arm for survival. The U.S. Coast Guard regulations additionally include minimum $\overline{GM}$ requirements for chemical and liquefied gas carriers.

Typical standards for the residual righting arm curve are shown on Fig. 39. Naval architects have long considered righting arm amplitude and range to be the best indices of stability. Nevertheless, for purposes of simplicity, the requirements for passenger ships laid down in the Regulations of the 1960 and 1974 International Conventions for Safety of Life at Sea, only called for minimum residual $\overline{GM}$'s and freeboards (both very small).

7.6 Special Requirements.

(a) Passenger Vessels—Traditional Factorial Standards. As previously stated, the factorial system of subdivision was intended to take into account the relative importance of the cargo and passenger carrying functions of a vessel. The intent was that vessels having a large volume of space below the margin line allocated to passengers and a greater total number of passengers on board, would require a greater degree of safety than a similar vessel with the entire volume of space under the margin line devoted to cargo and with fewer total passengers on board. They therefore devised two formulas to take these variations into account. The first is the *Criterion of Service,* and the second the *Factor of Subdivision.*

The formula for Criterion of Service uses length, number of passengers, total volume of the ship below the margin line, volume of the machinery space, and volume of the accommodation spaces below the margin line and combines them so that the lower the value of the criterion of service, the farther apart the watertight bulkheads may be spaced.

The formula for Factor of Subdivision uses factors of length and the Criterion of Service, and the result is a percentage running from 30 to 100 percent (0.3 to 1.0). This Factor of Subdivision establishes the permissible length between watertight bulkheads. A factor of 1.0 means the bulkheads may be spaced apart a distance equal to 100 percent of the floodable length. A factor of 0.3 means the spacing can only be 30 percent of the floodable length. For methods of determining the criterion of service and factor of subdivision and the special provision required in their application, the reader is referred to the U.S. Regulations which vary slightly and are more severe than the requirements of the SOLAS Conventions (46 CFR 73.10, 74.10-15).

(b) Permeabilities. Before the effects of flooding can be calculated, definite values for the permeabilities of the spaces involved must be assumed. The actual permeabilities in service are not accurately assessed and, in the case of cargo spaces, vary from space to space and from voyage to voyage. Consequently, all calculations of the affect of flooding based on the assumed permeabilities are unavoidably only approximations.

All criteria, with the exception of the traditional regulations for subdivision (not damaged stability) of passenger vessels on international voyages, and the regulation for permeability of cargo spaces for offshore supply vessels, assume a permeability for individual spaces as given in Table 5.

Table 5—Assumed Permeabilities

	Permeability Percent
Appropriated to cargo hold or stores	60
Appropriated to accommodation and voids	95
Appropriated to machinery	85
Appropriated for consumable liquids (using the value resulting in the most severe requirement)	0 to 95
Appropriated for liquid cargo tanks	0 or 95

The two table values of permeability for consumable liquid and liquid cargo tanks were put in for a specific reason. In vessels with high side tanks extending well above the waterline, for example, the stability effect of run off from initially full tanks (zero permeability), may be worse than that due to the ingress of damage water if the tanks are initially empty, i.e., (95 permeability). It is particularly important to investigate the stability effect of tanks having either zero or 95 permability during the period between initial damage and the final equalization. See Section 4.8. For example, transverse pairs of side tanks located outboard, port and starboard, which are interconnected by equalizing ducts and in which the tops of the tanks are below the waterline, can cause a large $\overline{GM}$ loss due to free surface during the time the tanks are being filled from the sea. This could conceivably cause the vessel to capsize before the tanks are filled and equalized.

In all cases where spaces between main transverse watertight bulkheads are occupied by spaces having different permabilities, an average permeability is used based on the percentage of the total space occupied by each category or permeability.

On offshore supply vessels the permeability of dry cargo spaces is assumed to be 95.

Volume and surface permeabilities are normally required to be the same. However, most criteria make a general statement that higher surface permeabilities should be assumed in respect of spaces which, in the vicinity of the damaged waterplane, contain no substantial quantity of accommodation or machinery, and spaces which are not generally occupied by any amount of cargo or stores. The maximum assumed surface permeability need not exceed 95.

All regulations, with the exception of the alternate equivalent passenger vessel regulations (Section 8) are silent on the matter of varying permeabilities at varying drafts. The Maritime Administration does, however, state that the permeabilities given in this section are average permeabilities and that the permeabilities should be routinely chosen so as to agree with the vessel's operating condition. For example, if the vessel has a cargo hold essentially empty in a light condition, they recommend a permeability of 95 rather than 60.

The regulations for bulk chemical and liquefied gas carriers both state that it shall be assumed that all liquids that are in a tank prior to damage have been completely replaced by salt water after damage. Other regulations are silent on this point, though the substitution seems to be implied. The tanker regulation makes the statement that the permeability of partially filled compartments shall be consistent with the amount of liquid carried.

While all regulations for damaged stability call for an investigation at a range of operating drafts, only the new equivalent passenger vessel regulations makes a provision for varying the permeability of cargo spaces depending upon the draft. See Section 8.

For some time, it has been suspected that containerships, roll-on roll-off ships and barge-carrying ships have higher permeabilities in their cargo holds than traditional bulk cargo ships. In two recent studies sponsored by the Coast Guard and performed by the Maritime Administration, containerships had average permeabilities of 75, with a value forward of 80, a value amidship of 70, and a value aft of 75. The assumption was made that the containers were nontight and their interiors were flooded. The differences in values can be accounted for by the flare of the hulls forward and aft, with a greater percentage of the width of the holds not being occupied by containers.

On roll-on, roll-off ships with containers stacked on deck the permeabilities were 80 and with the containers rolled on and left on a chassis the permeability was 90. On the barge-carrying ships the cargo holds with barges assumed to be watertight, had a permeability of only 30, but with the barges not assumed to be watertight, the permeability of the space was 76.

No changes in U.S. regulations or international agreements have as yet resulted from the above studies. However, the Maritime Administration adopted a standard of 70 for container holds and for Ro-Ro ships a value of 80 for containers stowed on deck and 90 for containers on wheels.

The permeability of all spaces and particularly that of cargo spaces tends to be higher in the upper parts of the spaces. In accommodation and machinery spaces, this variation may not be enough to affect seriously the validity of calculations based on a uniform value. However, in cargo spaces, calculations based on a uniform value may grossly underestimate the $\overline{GM}$ loss.

Because of the variety in general cargo loadings, it is impracticable to attempt to account accurately for these variations. However, vertical variations in the permeability of cargo spaces may be compensated for partially by assuming, when calculating the available $\overline{GM}$, that the cargo is at the homogeneous center even when actually it may be only in the lower part of the space. In this way, underestimating the available intact $\overline{GM}$ tends to compensate for the underestimate in the $\overline{GM}$ loss due to disregarding the actual cargo distribution.

In determining the floodable length of passenger vessels on international voyages, a uniform average permeability is used throughout the whole length of

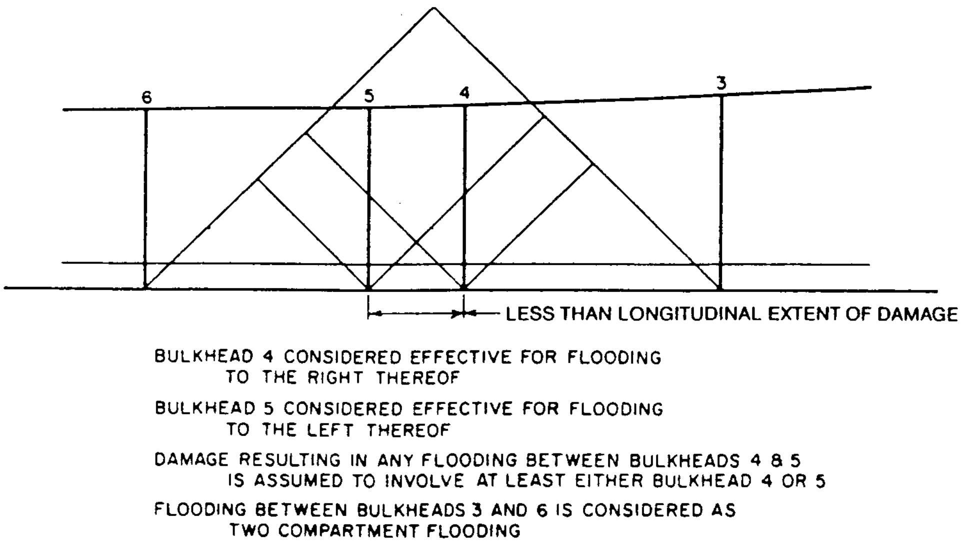


Fig. 40 Minimum spacing of bulkheads

each of the following portions of the vessel below the margin line:

1. The machinery space.
2. The portion forward of the machinery space.
3. The portion aft of the machinery space.

Formulas are given in the U.S. and SOLAS Regulations for determining the permeability in each of these areas. The assumption that permeabilities are uniform in each is illogical and unnecessary. More accurate results can be achieved readily by calculating the individual average permeability of each compartment.

(c) Minimum Spacing of Bulkheads. All criteria call for a minimum spacing of main transverse watertight bulkheads if two adjacent bulkheads are to be considered intact with the exception of the Regulations for Offshore Supply Vessels. This minimum distance is equal to the longitudinal extent of damage specified for the particular class of vessel. Since, for reasons of practicality, offshore supply vessels are only required to survive a collision which has a penetration of 760 mm (30 in.) it was evidently not felt necessary to put a minimum spacing on these vessels.

The method of handling bulkheads which are spaced closer together than the longitudinal extent of damage is illustrated in Fig. 40.

In U.S. passenger ship regulations the combined length of the forepeak compartment and the compartment just abaft the forepeak compartment in vessels over 100 m (330 ft) in length is required to be not greater than the permissible length. This causes difficulties in vessels that must meet a two or three-compartment standard, in that the after-most bulkhead is located so close to the forepeak bulkhead that the distance between them cannot comply with the requirement for the minimum spacing of bulkheads to be greater than the longitudinal extent of damage. This problem is corrected in the new Alternate Equivalent Passenger Vessel Regulations. (See Section 8.5).

(d) Recessed Bulkheads. In general, all criteria do not permit recessed bulkheads unless the entire recess is located inboard of the side of the vessel at a distance not less than the assumed transverse extent of damage. Fig. 41 shows permissible recessed bulkheads.

In offshore supply vessels where bulkheads in side tanks need to be extended only 760mm (30 in.) in from the shell, bulkheads recessed inboard of that point can be considered as main transverse watertight bulkheads. A bulkhead inboard of the side tank may be stepped, but the double bottom tank extending between the inboard transverse bulkhead and the outboard bulkhead must have its volume added to the volume of the outboard compartment.

It frequently is not recognized that a shaft alley may constitute a recess. If all parts of a shaft alley are inboard of the aforesaid one-fifth beam line, it may be regarded as providing intact buoyancy. However, if within a portion of its length a shaft alley is nearer to a vessel's side it should be regarded as liable to be damaged within that part of its length. In such case, it will flood for its entire length and therefore should be regarded as constituting a recess into the full length of the adjoining compartment or compartments which it penetrates.

(e) Stepped Bulkheads. From the viewpoint of safety it is desirable for bulkheads to be fabricated in a single plane. Steps increase the likelihood that a bulkhead may be damaged. Also the watertight portions of decks required by steps are liable to have their integrity violated by nontight penetrations made during the life of the vessel. This is because such portions of decks are liable not to be recognized as part of a vessel's watertight subdivision when such alterations are made. For this reason, it is important that the

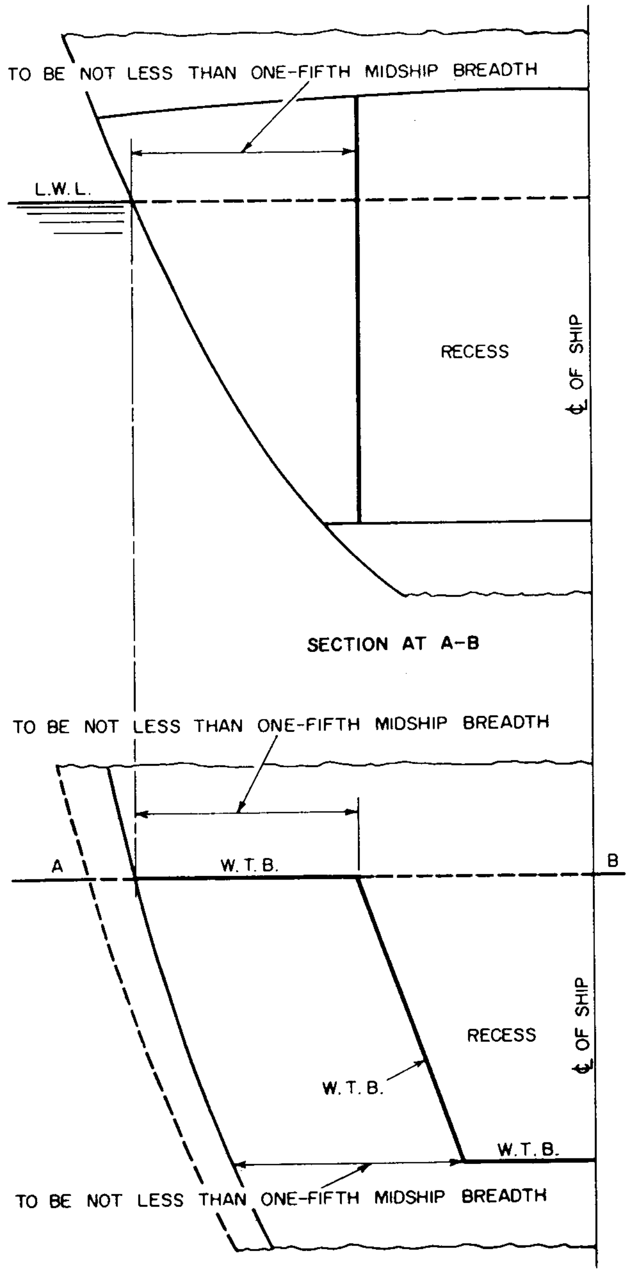


Fig. 41 Recessed bulkheads

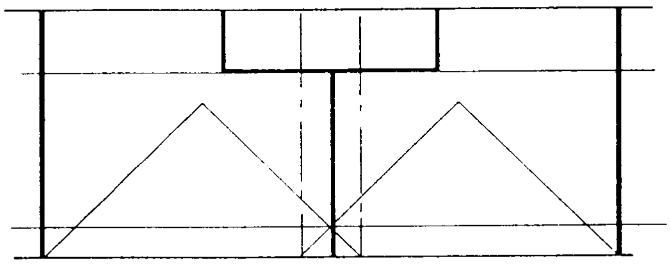


Fig. 42 Stepped bulkheads

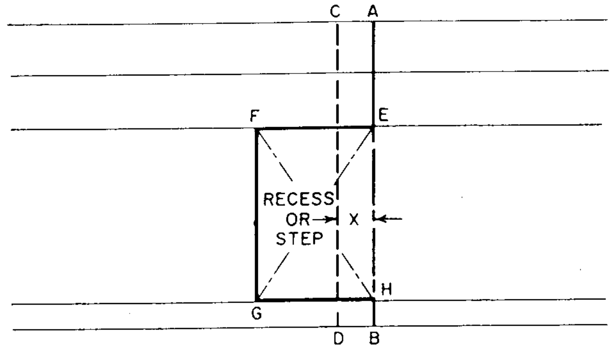


Fig. 43 Equivalent plane bulkhead

Bulkhead AB is recessed or stepped as shown. The location of the equivalent plane bulkhead is given by X = Volume $EFGH$/area A, where A is the sectional area to the margin line approximately midway between AB and CD

extent of any watertight steps be clearly indicated on a plan carried on the vessel.

U.S. Passenger Vessel Rules permit a main transverse bulkhead to be stepped under certain conditions. See 46 CFR 73.10, 74.10-15.

1. *The combined length* of the two compartments, separated by the bulkhead in question, does not exceed either 90 percent of the floodable length or twice the permissible length, except that in ships having a factor of subdivision greater than 0.9, the combined length of the two compartments in question shall not exceed the permissible length; or

2. *Additional subdivision* is provided in way of the step to maintain the same measure of safety as that secured by a plane bulkhead, Fig. 42; or

3. *Length of the compartment* over which the step extends does not exceed the permissible length corresponding to a margin line taken 7.5 cm (3 in.) below the step.

Where a bulkhead is stepped or recessed, an equivalent plane bulkhead (or bulkheads) is used. The usual case is illustrated in Fig. 43. Where additional subdivision is provided in way of the step, such as by stepping the bulkhead both ways, the appropriate equivalent plane bulkheads are as illustrated in Fig. 42.

Where the distance between equivalent plane bulkheads or that between transverse planes passing through the nearest portions of stepped bulkheads is less than the assumed longitudinal extent of damage, the bulkheads concerned are dealt with the same as are plane bulkheads at less than this spacing, as illustrated in Fig. 40.

When a main transverse watertight compartment contains local subdivision, and it can be shown that, after any assumed side damage of the required transverse and longitudinal extent, the whole volume of the main compartment will not be flooded, a proportionate allowance may be made in the permissible length otherwise required for the compartment by the passenger vessel factorial standards. The manner of allowing for these unflooded spaces is shown in Fig. 44. In the integer compartmentation standards there are obviously no reductions allowed in the minimum spacing of bulkheads and the intact buoyancy is taken care of by corrections to the volumes and centers of the lost buoyancy or mass and centers of the added weight.

(f) Independent Tanks, Bulk Chemical and Liquefied Gas Carriers. Detail requirements for the location of independent tanks in these classes of vessels with respect to distance from the ship's side or from the bottom are given in the U.S. Coast Guard Regulations and should be carefully checked by designers.

(g) Internal Non-watertight Compartmentation. Where internal divisions, particularly longitudinal bulkheads, are non-watertight, but are so constructed as to permit water only to leak through slowly when a space adjacent to the bulkhead is flooded, then the heeling moment of the water must be accounted for. A large mass of water may be retained on one side of the bulkhead for a considerable length of time before equalization on both sides of the bulkhead takes place.

Examples of such bulkheads are steel structural bulkheads built to A-0 fire classification standards with metal joiner doors, and steel insulated bulkheads in refrigerated spaces. So called "flooding plugs" designed to blowout at a nominal low head are often installed in such bulkheads, but are not looked upon with favor because there may be sticking due to rust or excess paint and can often be blocked from opening by cargo carelessly stowed against them.

The vessel must have sufficient residual stability after damage that the heeling moments resulting from such bulkheads will not capsize the ship or reduce its survival capability below the criteria requirements during the time that equalization takes place.

(h) Superstructures. The many standards for damaged stability have never been completely consistent regarding the effect of superstructures on residual stability of damaged vessels. It is agreed and generally accepted that a superstructure directly over the location of collision damage can also be opened to the sea by the damage and its buoyancy in that area must be neglected in calculating righting moments. However, the use of terminology and practice from the load line conventions confuses the issues, i.e., the requirement that houses have a certain required deck height to be considered effective. *All* enclosures above the bulkhead deck, whether they are trunks or enclosures at the sides or center, only are effective if their buoyancy is maintained intact by watertight structures and watertight closures (weathertight if they are not submerged at the equilibrium waterline and come into effect only in the residual range of stability). Common sense in including only the buoyancy of those structures that are demonstrably effective in providing buoyancy moments in a heeled condition should be, and generally is, the basic criterion used by the competent naval architect.

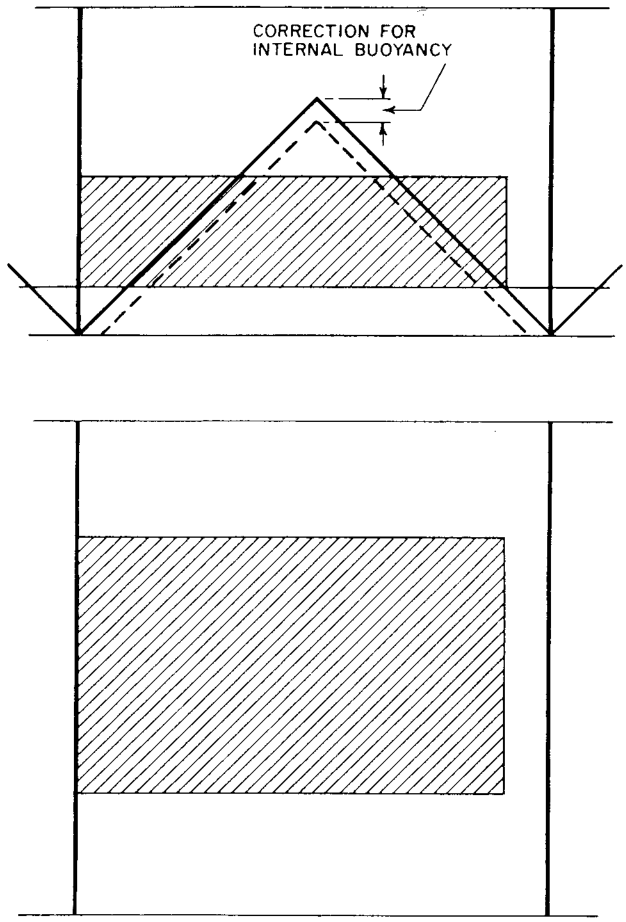


Fig. 44 Correction for internal buoyancy

(i) Unsymmetrical Flooding is required to be kept to a minimum consistent with efficient arrangements. On passenger vessels on international voyages, where it is necessary to correct large angles of heel, the means adopted are required, where practicable, to be self-acting, but in any case, where controls to cross-flooding fittings are provided, they must be operable from above the bulkhead deck. The construction and arrangement of such fittings and of their controls, together with the estimated maximum heel before equalization, are subject to special approval. The time for equalization to acceptable heel limits, as given by the Solda equation (Section 4.8), is not permitted to be more than 15 min. On all other vessels, the equalizing arrangements, where required, must not depend upon either manual or automatic operation of valves or similar appliances. (Note that in Section 8 the equalization time for the alternate equivalent subdivision regulations is reduced to 10 min.).

Even though means for equalizing unsymmetrical intact buoyancy or for flooding of unfavorable symmetrical intact buoyancy are provided, it is important to consider the intermediate condition of the ship after damage, but prior to completion of final flooding. With the exception of those cases where the use of large unobstructed openings such as open passages or cofferdams is possible, it must be assumed that the ship will experience a transient condition during which primary flooding becomes essentially complete before equalization has occurred.

Survival of this transient condition requires: (*a*) that the static heel be not so great as to eliminate the hydrostatic head necessary for compensatory flooding; (*b*) that the static heel be not so great as to result in the progressive extension of the flooding (submergence of the margin line during an intermediate stage of flooding is permissible provided there is sufficient watertight integrity above the margin line to insure that progressive extension of flooding will not occur); and (*c*) that the range of stability in the transient condition be sufficient for the vessel to survive the compensatory period.

Where compensatory flooding or equalization is necessary, calculations should be made to ascertain that requirements (*a*) and (*b*) are met. Unless transient condition $\overline{GM}$ and freeboard are large enough obviously to provide a sufficient range of stability, (*c*) should also be checked by calculation of righting arms in the transient damaged condition.

(*j*) *Dump Valves.* Where flume stabilizer tanks or swimming pools are fitted with dump or flooding valves and it is desired to credit these valves in determining the final stage of flooding, the maximum time for all required equalization action plus such dumping or flooding must not be more than 15 min. (10 min. in equivalent passenger vessel regulations).

Section 8
Alternate Equivalent Passenger Vessel Regulations

8.1 General. The loss of the *Andrea Doria* in 1956 not only caused a complete discrediting of the theory that tanks designed for the carriage of bunker oil could or would be filled with ballast water to meet damaged stability requirements, but it caused a new critical look to be taken at all of the assumptions implicit in the standards for subdivision and damage stability contained in the existing international passenger vessel regulations.

Among the weaknesses found in the then existing standards, were:

(*a*) The formulas for Criterion of Service involving the relationship between the volume of different spaces within the ship's hull were out of date. Improvements in design had permitted higher power within less volume in the machinery spaces, and modern requirements for more spacious accommodations resulted in more passenger space above the bulkhead deck. The safety standard applied to ships primarily carrying passengers had therefore depreciated.

(*b*) The existing regulations did not take into account the fact that for any given bulkhead arrangement quite different extents of flooding could occur as a result of varying assumed damage lengths.

(*c*) The method employed in the existing regulations did not take into full account the effect of ship proportions, of varying drafts and permeabilities, or of stability when flooded, on the degree of safety. Two vessels might be judged equally safe although they might have very different actual capabilities to survive.

The realization of these and other weaknesses during the 1960 SOLAS Conference gave impetus to the consideration by IMCO of possible new regulations based on probability principles.

As explained by Robertson, et al (1974), casualty data regarding hull damages were collected and analyzed. Voyage data relative to loading conditions, draft, operating $\overline{GM}$, etc., were also sought and analyzed. Model tests simulating damaged ships in a seaway were conducted. In 1967 an ad hoc group was assigned to prepare new regulations based upon these studies. Several different forms of regulations were considered. In 1971, after extensive study of possible regulations, principally involving separate floodable length and damage stability calculations, a revised format based directly on use only of damage stability calculations was submitted. This formed the basis for the new regulations as now adopted. See Appendix 1 of Robertson, et al (1974).

While these new regulations are administratively equivalent and alternative to those of Chapter II of the 1960 International Convention for the Safety of Life at Sea, and provide on the average about the same degree of safety, they are considered vastly superior thereto from the viewpoint of logic and consistency. Calling the new provisions "equivalent" permits a period during which administrations may assess and gain familiarity with them prior to adoption by the formal ratification and amendment procedures of the Safety of Life at Sea Convention.

8.2 Basis of the new regulations. Fundamentally, three probabilities relate to subdivision and damage stability requirements:

(*a*) Probability that a ship may be damaged.

(*b*) If the ship is damaged, the probability as to location and extent of flooding.

(*c*) Probability that the ship may survive such flooding.

The probability that a ship may be damaged is relevant to the required degree of ability to survive damage and to the determination of insurance premiums. It is conditional upon navigational conditions, traffic density, visibility, effectiveness and reliability of navigational aids, ship speeds and maneuvering capabilities, and the judgment, competence and dependability of personnel involved.

From the purely theoretical viewpoint, evaluation of the effect of each of these factors would permit determination of probability of loss for each ship, or at least for each class of ship. Practically, the available statistical and other necessary information is not sufficient for this purpose. However, some useful deductions are possible. Examination of casualty data confirms that damages due to collisions (and strandings) are more prevalent in harbor approach areas and areas of especially high traffic density such as the English Channel. Ships whose operation is principally or exclusively in such areas are more likely to be damaged. Passenger ships in this category tend to carry a higher density of persons than ships on longer voyages outside such waters. In the new regulations, the required degree of safety is dependent principally upon the number of persons, and is increased when the density is such that all persons cannot be accommodated in lifeboats.

So long as a ship remains undamaged, there is no need whatsoever for any subdivision or damage stability. The need for evaluation of subdivision and damage stability stems from the knowledge that risk of damage does exist, and this leads to consideration of probabilities 2 and 3.

Probability 2 is dependent upon the location and extent of hull damage and upon the arrangement of watertight divisions within the ship. This general relationship was recognized as early as 1919, and a relatively rigorous procedure for dealing with it was first presented by Wendel (1960).

Probability 3 is dependent upon buoyancy and stability in the flooded condition. This in turn is subject to the following variable factors:

(a) The location and extent of flooding.
(b) The permeability of flooded spaces.
(c) The draft and stability before flooding.
(d) Applied forces and moments.

Data for a total of approximately 860 ship damage cases attributable to strandings and collisions were compiled. After preliminary review, it was decided that probability as to location and extent of damage might best be evaluated by limiting study to collision cases involving only passenger and cargo ships, excluding tankers. Data on vertical location and extent were also available, but it did not seem feasible to deal with these variables probabilistically.

The probability of survival in any flooded condition is also dependent upon the probability in respect to applied forces and moments in that condition. These may be due to wind and sea, or to location or movement of tankage, persons, or other weights.

To evaluate the relationship between sea state, stability and buoyancy when flooded, and survival probability, damage stability model tests in waves were conducted. Test models included a long-voyage passenger-cargo type ship (Middleton and Numata, 1970) and a short-voyage passenger-vehicle ferry (Bird and Brown, 1973). Supplemental damage stability tests of simplified models dealing particularly with the effects of variations in beam-depth ratio and of internal arrangements were also conducted (Stahlschmidt, 1972.) The mechanism of capsize observed in all tests was similar in similar situations. Despite the wide difference in ship type and proportions, the references showed some degree of agreement as to the stability necessary to survive a given sea state. For both of these series of tests, there was sometimes a substantial difference between the stability necessary to avoid capsize when the damage was to windward and when it was to leeward. However, with that exception, in any given condition, the difference between the stability at which repeated capsizes occurred and that at which they did not occur was small. Therefore, for simplicity, the values of stability necessary for survival at any sea state were averaged and treated as deterministic rather than as random variables, as might theoretically be expected. The model tests were very interesting and the references cited provide much food for thought.

To evaluate actual service variations in draft and permeability and in stability before flooding, relevant ship voyage data were reviewed. The ships for which the most complete data were available were of passenger-cargo and cruise type. Some data on the operation of both short-voyage passenger-vehicle type ships and long-voyage cargo-passenger ships were also included.

Draft distributions were found to differ considerably. Despite these variations, the new regulations assume a standard form of draft distribution to apply to all passenger ships. While this standard draft distribution was based upon the ship draft data, its median value is somewhat higher than the average median of the reported values. Use of such a single standardized form of assumed draft distribution is considered justified for the following reasons:

(a) For uniformity in administration and because of lack of a clear indication as to how a ship's service draft distribution might better be anticipated in the design state.

(b) Because example calculations have indicated that the Subdivision Index A, according to Regulation 6 of the new regulations, is not too sensitive to differences in the form of draft distribution.

The ship voyage data also included information on the kind and quantity of cargo carried, on the cargo space volume, and on the percentage of that volume occupied by cargo. Utilizing that information and other data, the average cargo space permeability for each

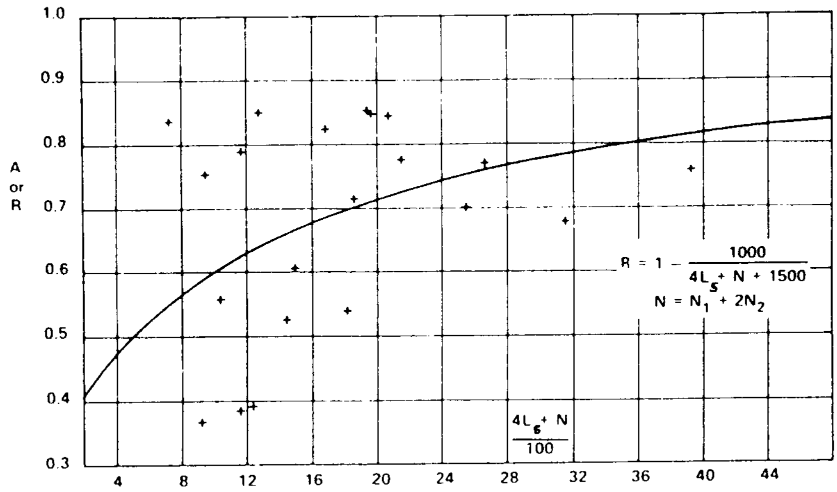


Fig. 45 Comparison of *R* with the calculated *A* values of existing ships which comply with Chapter II of the 1960 Safety Convention. L_s and N are as defined in Regulations 1(b) and 2(c) respectively

loading condition was estimated and related to the draft or drafts corresponding to that condition. As might be expected, the cargo space permeability at any draft is a variable. However, for purposes of simplifying the calculations, the cargo space permeability formula given by new Regulation 4(b) treats it as deterministic.

It may be demonstrated by means of probability theory that the probability of ship survival can be calculated as a sum of probabilities of its survival after flooding each single compartment, each group of two, three, etc., adjacent compartments multiplied, respectively, by the probabilities of damage leading to such flooding.

The new regulations prescribe that a ship's Attained Subdivision Index *A* must be equal to or greater than its Required Subdivision Index *R*. *A* is equal to the summation over the ship's length of the expression Σaps, where

a accounts for the probability of damage as related to the position of the damage in the ship's length.

p evaluates the effect of the variation in longitudinal extent of damage on the probability that only the compartment or group of compartments under consideration may be flooded.

s evaluates the effect of freeboard, stability, and heel in the final flooded condition for the compartment or group of compartments under consideration.

If it were possible to accomplish this summation, including evaluation of each of the terms, rigorously and completely, *A* would be the probability that the ship would survive any and all damages resulting in breaching of the hull which might occur during her lifetime. However, for reasons already mentioned in the foregoing general discussion of the concept of the regulations and of the background studies, approximations and simplifications have been necessary. Therefore, *A* should be regarded not as the actual survival probability, but rather as a number which is dependent upon the assessable principal factors and which is approximately proportional to that probability.

The Required Subdivision Index *R* is dependent upon the length of the ship and the number of persons, and is thus related to the property and lives at stake in case of a casualty. This relationship is complex and not explicit. Furthermore, it is dependent upon the effect of subdivision and stability provisions on economic and other operational conditions. For the time being, a suitable level for *R* could only be determined from consideration of the *A* values of existing ships calculated according to the new regulations. Figure 45 shows the *A* values of some existing ships that comply with the 1960 regulations and *R* as contained in the new regulations. The wide scatter in the *A* values of existing ships is at first startling and was a source of considerable discussion. However, it is not so surprising when one considers the illogical aspects of the 1960 SOLAS regulations.

The relation between *R* and the *A* values of existing ships reflects the decision reached early in the IMO Subcommittee deliberations that the average level of safety attained under the new regulations should only be equal to that attained under the 1960 SOLAS regulations. This decision was not consistent with the views of the U. S. and some other delegations to the 1960 Safety of Life at Sea Conference, who thought a higher standard was practical and necessary. However, it contributed appreciably to establishment of the degree of rapport within the the Subcommittee essential to completion of the very extensive and drawn-out work culminating in these new regulations. Many believe that a higher standard of safety is practicable and are hopeful that experience in design of ships to the new regulations will lead to eventual agreement on this point.

In addition, such experience should lead to procedural improvements in the provisions of the regulations and related calculations. It is hoped that adequate related systematic study of casualties, of ship operating data, of waves and other sources of upsetting moments, and of relevant ship response will be continued. While these new regulations, *per se*, apply only to passenger ships, the principles upon which they are based are such that similar procedures may well be developed, not only for evaluation of the subdivision of other types of ships, but also for logical evaluation and control of other damage-related ship risks.

These alternate regulations have not as yet been incorporated in the published U.S. Coast Guard Regulations, although they are accepted and endorsed by the U.S. Coast Guard. The complete regulations are given in IMO Resolution A265 (VIII), and explanatory notes to the regulations are given in IMO MSC/CIRC. 153. Both of these are reproduced in the Coast Guard Commandant's International Series (1974). Further explanation of the reasoning behind the regulations is given in Robertson, et al (1974).

There is general acceptance among the leading authorities of the maritime nations that the probability principles on which the alternate regulations are based are sound and their application to other classes of vessels offers the possibility of obtaining increased safety without substantially increasing construction and operating costs. Since the promulgation of these alternative regulations occurred at the same time as the passenger airlines were sweeping the bulk of ocean going passenger vessels from the seas, few naval architects have had any reason to use and understand these regulations and to explore the possibilities of improving the safety of other classes of vessels by their use. It is hoped that in the coming years, this situation will gradually change and experience will lead to the adoption of these principles for a larger portion of the world's seagoing fleet. See Tagg (1982).

8.3 Definitions. Regulation 1 of the IMO new equivalent subdivision regulations gives the following definitions. For the purpose of these Regulations, unless expressly provided otherwise:

(a) (i) A 'subdivision load line' is a waterline used in determining the subdivision of the ship; and
(ii) the 'deepest subdivision load line' is the waterline which corresponds to the greatest draught permitted by the subdivision requirements which are applicable.

(b) the 'subdivision length of the ship' (L_s) is the extreme moulded length of that part of the ship below the immersion limit line.

In effect, the subdivision length L_s is the molded overall length of the buoyant part of the ship throughout which damage may affect buoyancy and stability. Thus, in a flush deck vessel, the length is measured between the intersections of the deck with the stem and stern. In vessels with raised forecastles and/or poops, the length is measured between the intersection of the forecastle deck with the bow and the intersection of the poop deck with the stern. In contrast to the length, as defined in the U.S. traditional passenger ship regulations, it is virtually always greater and is unaffected by changes in subdivision draft. While the "subdivision length of the ship" L_s is always used in the formulas for required and attained subdivision indices, it is common practice to use hydrostatic data from lines plans drawn with end ordinates at the load waterline or the ship's perpendiculars. This practice is accepted because it is conservative. Neglecting the buoyancy between the end ordinates and the end points for subdivision length, results in giving a trim for compartments inboard of the ends which is greater than the actual trim. In cases where the attained index is marginally below the required index using the end ordinates on the lines plan, modification can be made treating the added buoyancy at the ends as appendages.

(c) 'midlength' is the midpoint of the subdivision length of the ship (L_s).

(d) (i) the 'breadth' (B_1) is the extreme moulded breadth of the ship at midlength at or below the deepest subdivision load line;
(ii) the 'breadth' (B_2) is the extreme moulded breadth of the ship at midlength at the relevant bulkhead deck.

Together with freeboard (and the ship's form) B_2 affects the heel line at which the "relevant bulkhead deck" will immerse. It is possible for more than one deck to be the "relevant bulkhead deck". Therefore in the case of some ship's having tumblehome or flare to the topsides, B_2 may have more than one value.

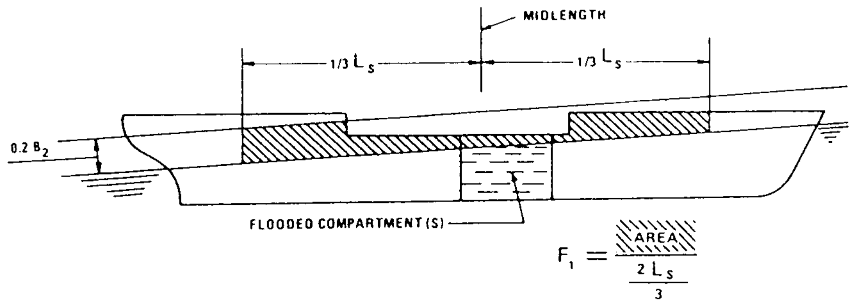
(e) The 'relevant bulkhead deck' is the uppermost deck which, together with the watertight bulkheads bounding the extent of flooding under consideration and the shell of the ship, defines the limit of watertight integrity in the flooded condition.

Where watertight bulkheads and the associated ship's shell are watertight to different levels in different parts of the ship, the "relevant bulkhead deck" in respect to some flooding situations will be different from that of other flooding situations.

(f) The 'immersion limit line' at any point in L_s is defined by the highest relevant bulkhead deck at side at that point.

(g) The 'draught' (d_i) is the vertical distance from the moulded base line at midlength to the waterline in question.

(i) The 'subdivision draught' (d_s) is the sub-



THE DISTANCE 0.2 B_2 MAY BE MEASURED PERPENDICULAR TO THE DAMAGE WATERLINE, OR PERPENDICULAR TO THE SUBDIVISION LOAD LINE. THE DIFFERENCE IS NEGLIGIBLE FOR REGULATORY PURPOSES.

Fig. 46 Illustration of "effective mean damage freeboard" (F_1)—Regulation 1 (h)

division load line in question.

(ii) The 'lightest service draught' (d_o) is the service draught corresponding to the lightest anticipated loading and associated tankage, including, however, such ballast as may be necessary for stability and/or immersion.

(iii) Intermediate draughts between d_s and d_o are:

$$d_1 = d_s - 2/3(d_s - d_o)$$

$$d_2 = d_s - 1/3(d_s - d_o)$$

$$d_3 = d_s - 1/6(d_s - d_o)$$

(h) The 'effective mean damage freeboard' (F_1) is equal to the projected area of that part of the ship taken in the upright position between the relevant bulkhead deck and the damage waterline and between $1/3L_s$ forward and abaft the midlength divided by $2/3L_s$. In making this calculation no part of the area which is more than $0.2B_2$ above the damage waterline shall be included. However, if there are stairways or other openings in the bulkhead deck through which serious downflooding could occur F_1 shall be taken as not more than $1/3(B_2 \tan \theta_F)$, where θ_F is the angle at which such openings would be immersed.

The effective mean damage freeboard and the limitations on F_1 are illustrated in Figures 46 and 47.

(i) The 'permeability' (μ) of a space is the proportion of the immersed volume of that space which can be occupied by water."

8.4 Required Subdivision Index. IMO regulation number 2 reads as follows:

(a) To provide for buoyancy and stability after collision or other damage, ships shall have sufficient intact stability and be as efficiently subdivided as is possible having regard to the nature of the service for which they are intended.

(b) The subdivision of a ship is considered sufficient if:

(i) the stability of the ship in damaged condition meets the requirements of Regulation 5 [Section 8.7]; *and*

(ii) the attained Subdivision Index A according to Regulations 6 and 7 [Sections 8.8, 8.9] *is not less than the required Subdivision Index R calculated in accordance with paragraph (c) of this Regulation.*

(c) The degree of subdivision is determined by the required Subdivision Index R, as follows:

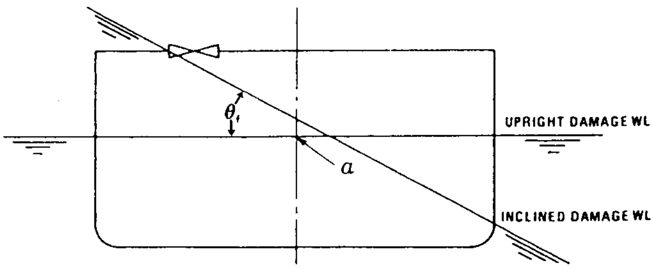
$$R = 1 - \frac{1000}{4L_s + N + 1500} \quad (m)$$

$$R = 1 - \frac{1000}{1.22L_s + N + 1500} \quad (ft) \qquad (1)$$

Where:

$$N = N_1 + 2N_2$$

N_1 = *number of persons for whom life boats are provided.*



THE ADMINISTRATION MAY DETERMINE IN EACH CASE IF THE INCLINED DAMAGE WL CAN BE ASSUMED TO PASS THROUGH THE INTERSECTION POINT a, WITH NEGLIGIBLE DIFFERENCE IN θ_f

F_1 SHALL NOT BE TAKEN AS MORE THAN $\frac{1}{3}$ B_2 TAN θ_f WHERE θ_f IS THE ANGLE AT WHICH STAIRWAY OR OTHER OPENINGS IN THE BULKHEAD DECK ARE IMMERSED.

Fig. 47 Illustration of limit on F_1 imposed by openings in the bulkhead deck

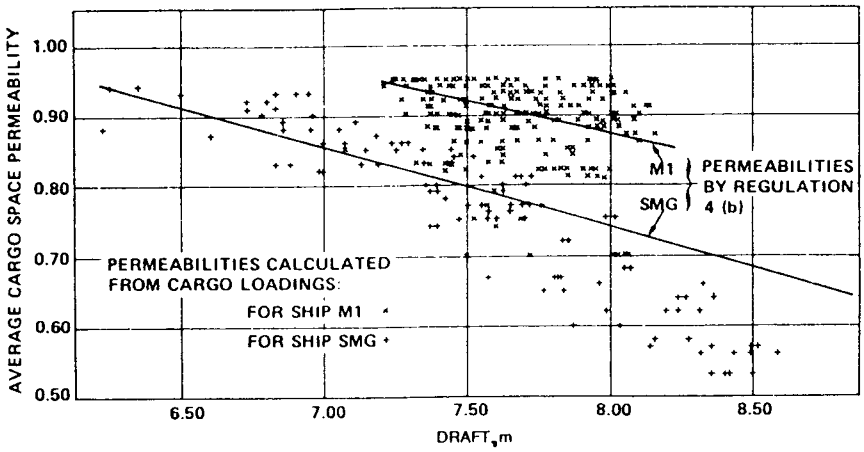


Fig. 48 Permeability vs. draft for two passenger-cargo ships: M1—180 m, 557 pass.; SMG—156 m, 121 pass

N_2 = number of persons (including officers and crew) that the ship is permitted to carry in excess of N_1.

(d) Where the conditions of service are such that compliance with paragraph (b) of this Regulation on the basis of $N = N_1 + 2N_2$ is impracticable and where the Administration considers that a suitably reduced degree of hazard exists, a lesser value of N may be taken but in no case less than $N = N_1 + N_2$.

As an example of how the Required Subdivision Index R increases as the number of passengers increases and also as the length increases, the following data are given:

REQUIRED SUBDIVISION INDEX R

Length of Ship	500 Pass.	1000 Pass.	1500 Pass.
122 m (400 ft)	0.598	0.665	0.713
183 m (600 ft)	0.634	0.691	0.732
244 m (800 ft)	0.664	0.712	0.748

It will be seen later that the higher the subdivision index, the greater the subdivision requirements. Obviously, the increase due to the number of passengers is intended to take into account the need for greater safety with greater numbers; the increase due to length, takes into account the ability of a longer ship to be subdivided in such a way as to decrease the probability of damage occurring that will sink the ship.

8.5 Special Requirements. The IMO Regulations have a number of regulations concerning double bottoms and bulkhead arrangements and watertightness, generally consistent with the existing U.S. Regulations. (See IMO Regulations 3 and 9 through 19). The major variation occurs in Regulation 3, concerning the bulkhead just abaft the forepeak bulkhead, which only requires that the forepeak and the next adjacent compartment have an "s" value of not less than one. Also, an additional requirement is that the distance between the forepeak bulkhead and the next bulkhead shall not be less than the required longitudinal extent of damage.

8.6 Permeability. The permeabilities of various spaces set forth in IMO Regulation 4 are as follows:

(a) Spaces	*Permeability (μ)*
Appropriated as accommodation for passenger and crew, or other spaces not specifically herein designated	*0.95*
Appropriated for machinery	*0.85*
Normally occupied by stores	*0.60*
Intended for consumable liquids	*0.00 or 0.95**

** whichever results in the more severe requirement.*

(b) The permeability μ of any space appropriated for cargo shall be assumed to vary with the draught before damage in such a way that for any initial draught d_i the permeability μ_i of any cargo space shall be taken as:

$$\mu_i = 1.00 - \frac{1.2(d_i - d_o)}{d_s} - \frac{0.05(d_s - d_i)}{(d_s - d_o)}$$

but not more than 0.95 nor less than 0.60.

It should be noted that here, for the first time, a subdivision and damage stability standard varies the permeability used for a given compartment depending on the draft, assigning a higher permeability at the lower drafts. This is consistent with the fact that cargo holds generally will not be filled with cargo at the light drafts. Fig. 48 shows a plot of permeability versus draft calculated from paragraph (*b*) above for two of the ships analyzed in preparing the regulations. The detail permeability calculations for these ships on various voyages are also indicated.

It will also be noted that the use of average permeabilities forward and aft of the machinery space is eliminated and only the individual permeabilities for each space are used.

8.7 Required Subdivision and Damage Stability. The requirements for subdivision and damaged stability are given in this section and in Sections 8.8 and 8.9, corresponding to IMO Regulations 5, 6 and 7. Regulation 5 is set forth below:

(a) Sufficient intact stability shall be provided in all service conditions so as to enable the ship to comply with the provisions of this Regulation. Before certification of the ship, the Administration shall be satisfied that the required intact stability can practicably be obtained in service.

(b) (i) All ships shall be so designed as to comply with the provisions of this Regulation in the event of flooding due to one side damage with a penetration of $0.2B_1$ *from the ship's side at right angles to the centerline at the level of the subdivision load line and a longitudinal extent of 3m(9.8 ft) +* $0.03L_s$*, or 11 m(36 ft) whichever is the less, occurring anywhere in the ship's length, but not including a transverse bulkhead. However, where a bulkhead is stepped it shall be assumed as subject to damage.*

(ii) Ships for which N is more than 600 shall additionally be able to comply with this Regulation in the event of flooding, due to side damage including transverse bulkheads occurring anywhere within a length equal to (N/600 − 1.00)L_s*, measured from the forward terminal of* L_s*, where N is as defined in Regulation 2(c) and (d). The value of (N/600 − 1.00) shall not be more than one.*

(iii) In any calculation required under this paragraph, the damage shall be assumed to extend from the base line upwards without limit. However, if flooding due to a lesser extent of damage either vertically, transversely or longitudinally results in a higher necessary intact metacentric height, such a lesser extent of damage shall be assumed. In all cases, however, only one breach in the hull and only one free surface need be assumed. For the purpose of assessing heel prior to equalization, the bulkheads and deck bounding refrigerated spaces and other decks or inner divisions which in the opinion of the Administration are likely to remain sufficiently watertight after damage, shall be regarded as limiting flooding. Otherwise, flooding shall be assumed as limited only by undamaged watertight structural divisions.

(c) (i) In the final stage of flooding:

(1) there shall be a positive metacentric height, $\overline{GM}$*, calculated by the constant displacement method and for the ship in upright condition, of at least*

$$\overline{GM} = 0.003\,\frac{B_2{}^2(N_1 + N_2)}{\Delta F_1} \quad or$$

$$\overline{GM} = 0.049\,\frac{B_2}{F_1} \quad (ft)$$

$$\overline{GM} = 0.015\,\frac{B_2}{F_1} \quad (m) \quad or$$

$\overline{GM}$ *= 0.05 m (2in.) whichever is the greater*

Where Δ *= displacement of the ship in the undamaged condition (in long tons or metric tons respectively);*

(2) the angle of heel in the case of one compartment flooding shall not exceed 7 deg. For the simultaneous flooding of two or more adjacent compartments, a heel of 12 deg may be permitted unless the Administration considers a lesser heel necessary to ensure an adequate amount and range of residual stability;

(3) except in way of the flooded compartment or compartments no part of the relevant bulkhead deck at side shall be immersed.

(ii) Unsymmetrical flooding shall be kept to a minimum consistent with efficient arrangements. If any equalizing arrangements are necessary to ensure that the angle of heel in the final stage of flooding does not exceed the limits specified in sub-paragraphs (i)(2) and (3) of this paragraph, these arrangements shall, where practicable, be self-acting. However, if controls are necessary, they shall be operable from above the highest relevant bulkhead deck. All such arrangements shall be acceptable to the Administration.

(iii) The Administration shall be satisfied that stability prior to equalization is sufficient. However, in no case shall the maximum heel before equalization exceed 20 deg. nor shall it result in progressive flooding. Additionally, the time for equalization of cross-connected

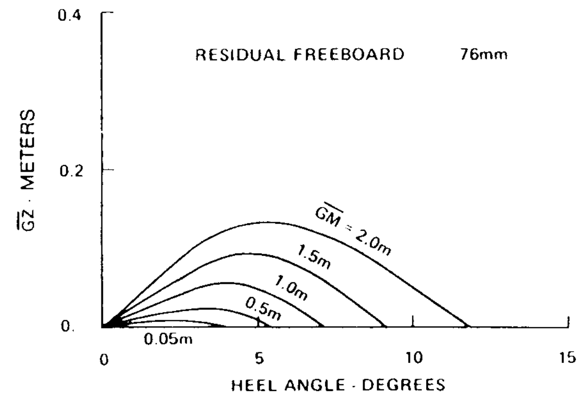


Fig. 49 $\overline{GZ}$ curves for a 100-m vehicle ferry

spaces to at least the limits specified in subparagraphs (i)(2) and (3) of this paragraph shall not exceed 10 min.

(iv) The Administration shall be satisfied that the residual stability is sufficient during intermediate flooding and that progressive flooding will not take place. Calculations relative thereto shall be in accordance with the provisions of subparagraph (b)(iii) of this Regulation, respecting the assumed extent of damage and resulting extent of flooding. Heel during intermediate flooding due either to negative metacentric height alone or in combination with unsymmetrical flooding shall not exceed 20 deg.

(b) Damage stability calculations performed in compliance with this Regulation shall be such as to take account of the form and the design characteristics of the ship and the arrangements, configuration and probable contents of the compartments considered to be flooded. In making calculations for heel prior to equalization and for equalization time, the flooding of that portion of the ship opened to the sea shall be assumed to be completed prior to commencement of equalization. For each initial draught condition, the ship shall be at the most unfavorable intact service trim anticipated at that draught having regard to the influence of the trim on the freeboard in the flooded condition.

(e) The intact metacentric height, and corresponding vertical center of gravity, necessary to provide compliance with the requirements specified in paragraphs (b) and (c) of this Regulation shall be determined for the operating range of draughts between d_s and d_o. If $(d_s - d_o)$ does not exceed 0.1 d_s, damage stability calculations may be made only for d_s and d_o, and the intermediate values may be obtained by linear interpolation. If $(d_s - d_o)$ exceeds 0.1 d_s, damage stability calculations shall also be made for at least one additional intermediate draught. However, in all cases, where there are vertical discontinuities in permeabilities or in free surfaces which may result in discontinuities in the necessary intact metacentric height, damage stability calculations shall be made for the corresponding draughts in order to define such discontinuities."

It will be seen from the above, particularly from the formulas given in subparagraph (c)(i)(1) that while 0.05 m (2 in.) of residual $\overline{GM}$ is permitted in the damaged condition, such a minimum $\overline{GM}$ must be accomplished by a high freeboard. For example, for a ship with a beam of 18.3 m (60 ft), a $\overline{GM}$ of 0.05m (2 in.) requires a freeboard of 5.5m (18 ft). Increasing the $\overline{GM}$ to 0.30 m (12 in.), permits the freeboard to be reduced to 0.9 m (2.95 ft).

While the traditional regulations permit a residual $\overline{GM}$ of 0.05 m (2 in.) with a freeboard after flooding of 0.075 m (3 in.), such a condition has virtually no survival probability. This is illustrated in Fig. 49.

Fig. 50 shows clearly the increase in initial $\overline{GM}$ required for a given ship by the provision in these regulations for increased residual $\overline{GM}$ after damage. The left hand curve in the figure shows the $\overline{GM}$ required for compartments 8 and 9 to comply with a two-compartment standard of subdivision under the existing Coast Guard rules. The curves on the right for compartments 10 and 11, and compartment 8, are the required $\overline{GM}$ under the equivalent regulations.

The alternate equivalent international passenger

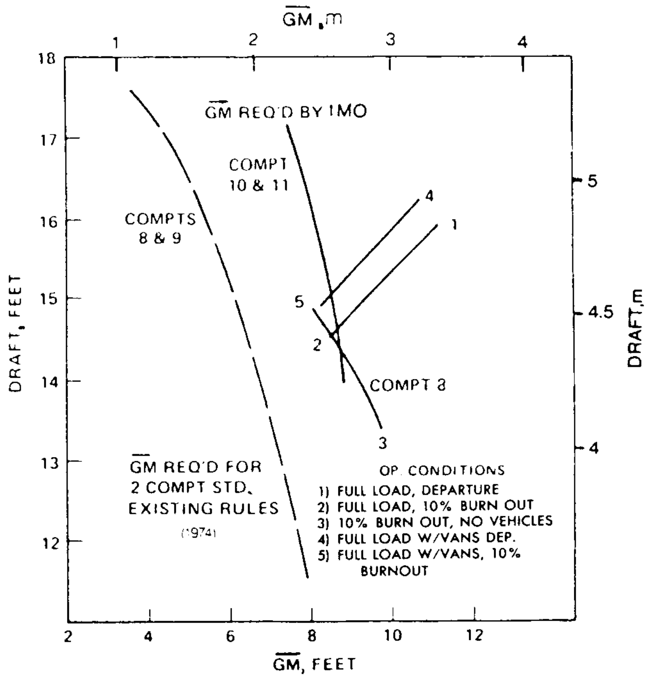


Fig. 50 Initial $\overline{GM}$ requirements for 128m 1420-ft.) passenger/vehicle ferry and available $\overline{GM}$s

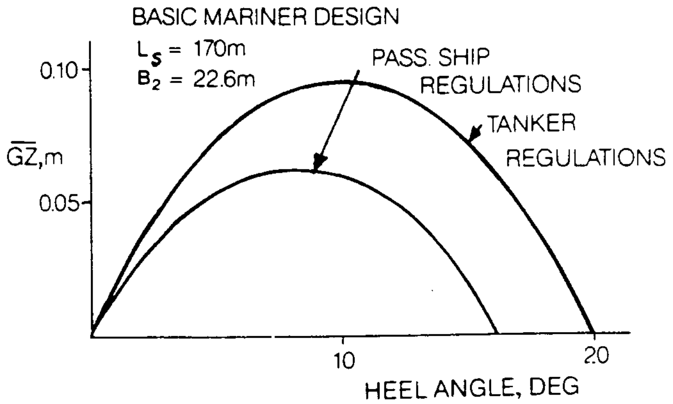


Fig. 51 Comparison of residual $\overline{GZ}$ curves required to meet survival criteria for tankers and for passenger ships under the new equivalent regulations

ship regulations specify only required residual freeboard and $\overline{GM}$ versus beam. This was done advisedly and because model tests both here and abroad indicated that capsizing of a damaged ship lying in a seaway is a quasi-static phenomenon, at least for passenger type ships. For such ships it appeared that freeboard, $\overline{GM}$ and beam, taken together, provided at least as good an index of survival as any simple righting arm and amplitude standard (Robertson, et al, 1974).

Fig. 51 shows that, as applied to the basic C4-5-1a *Mariner* design hull form, the new equivalent passenger ship regulations result in lesser righting arms than called for by the tanker regulations. It thus appears that the latter are more conservative. However, a much more extensive investigation and comparison would probably be necessary to be conclusive.

Subparagraphs (*b*)(i) and (*b*)(ii) above require all ships to meet a one-compartment standard, but when the number of passengers exceeds 1200, a two-compartment standard is required throughout. Between 600 and 1200 passengers, a portion of the ship, starting at the forward end is also required to meet a two-compartment standard. Fig. 52 illustrates this requirement.

8.8 Attained Subdivision Index. IMO Regulation 6 calls for the following:

(a) (i)
In addition to complying with Regulation 5 [Section 8.7] *the attained Subdivision Index A* shall be determined for the ship by formula (II):

$$A = \Sigma\ aps \qquad \text{(II)}$$

Where:

a accounts for the probability of damage as related to the position of the compartment in the ship's length,

p evaluates the effect of the variation in longitudinal extent of damage on the probability that only the compartment or group of compartments under consideration may be flooded, and

s evaluates the effect of freeboard, stability and heel in the final flooded condition for the compartment or group of compartments under consideration.

(ii) The summation indicated by formula (II) is taken over the ship's length for each compartment taken singly. To the extent that the related buoyancy and stability in the final condition of flooding are such that s is more than zero, the summation is also taken for all possible pairs of adjacent compartments, and may be taken for all possible groups of a higher number of adjacent compartment if it is found that such inclusion contributes to the value of the attained Subdivision Index A.

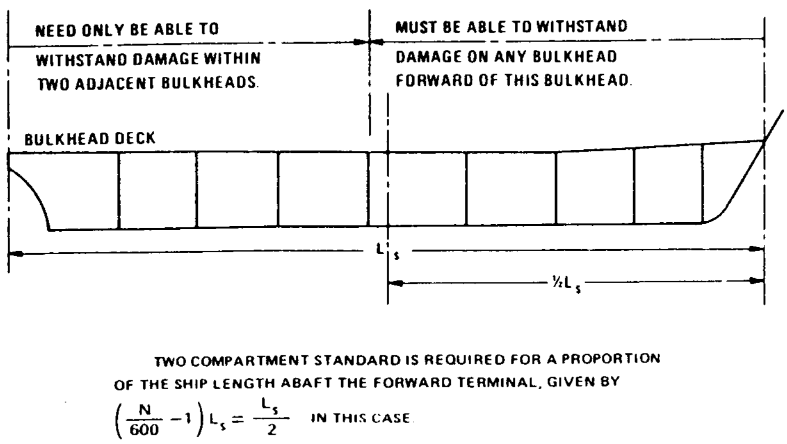


Fig. 52 Illustration of the application of Subparagraph 5(b)(ii) to a ship with $N = 900$

(iii) Wherever wing compartments are fitted and where the assumed damage used in the damage stability calculations according to Regulation 5 forming the basis for the s *calculation does not result in flooding of the associated inboard spaces,* p *shall be multiplied by* r *as determined in Regulation 7(b).*

IMO Regulation 6 continues by giving details of formulas for determining the above factors for each compartment and group of compartments:

a given by Formula III
p given by Formulas IV-VII
s given by Formulas VIII-IX

A detailed explanation of the meaning of the above factors a, p and s is given by Robertson, et al. (1974). Formula III for a given in the Regulation 6 corresponds to an assumed probability density function of longitudinal location of damage that has a constant value of 1.2 throughout the forward half, length and then decreases linearly to 0.4 at the extreme stern. This assumed density function conforms approximately to a histogram of damage location established from casualty records. Formula IV for p corresponds approximately to a density function of damage length which varies linearly from a maximum value at zero damage length to zero at a damage length of $0.24L_s$, but not more than 48 m (157 ft).

Finally, formula VIII for s is based on an empirical expression of the form,

$$s_i = k \left[\frac{F_e \, \overline{GM}_e}{B_2} \right]^{0.5}$$

where F_e is effective freeboard flooded and GM_e is effective metacentric height flooded. In the notation of the formula,

$$\frac{F_e}{\overline{GM}_e} = \frac{F_1}{\overline{GM}_R} - \frac{(B_2/2)}{\overline{MM}_s} \tan \theta$$

Although no simple formula applied to different types of ship could be expected to estimate closely the actual probability of survival, the accepted formula was found to give reasonable trends in comparison with model test results.

See IMO Regulation 6 for details of the formulas and their use in calculating the factors discussed above.

IMO Regulation 7 gives detailed requirements applicable to combined longitudinal and transverse subdivision.

After the basic IMO regulations were issued it was felt that certain additional explanatory notes were necessary. Accordingly, IMO Resolution A 265 (VIII), contained in C.G. Commandant's International Technical Series (1974), has attached to it a document, MSC/CIRC 153, that gives explanatory notes to the regulations. Part III of these notes titled "Guidance for Assembling Input Data and Structuring Output Data" contains valuable information which should be studied by anyone performing these calculations. Appendix II to the notes, titled "Combined Transverse and Longitudinal Subdivision," gives detailed information on nomenclature and methods of calculating values of p and a for combined longitudinal and transverse subdivision. Methods of handling recesses are also discussed in Appendix II.

In case of an actual application of the Alternate Equivalent Passenger Vessel Regulations the designer is advised to refer to the current IMO publications for up-to-date guidance information on the practical application of the regulations, as well as for possible changes and extensions to other ship types.

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