PRINCIPLES
OF
WARSHIP CONSTRUCTION
AND
DAMAGE CONTROL

A treatise on the fundamental principles of naval architecture, warship design and construction, and the control of hull damage especially prepared to furnish in compact form the information required by the operating personnel of the U. S. Navy.

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CHAPTER XI

CONTROL OF HULL DAMAGE

Section A—General

11-1. General.

We have noted that the most complete protection and compartmentation attainable cannot be relied upon to prevent serious effects of hull damage under the most severe conditions. Further, we have seen how other considerations limit the amount of protection and compartmentation on a battleship and how conflicting demands preclude the provision of any protection or satisfactory compartmentation of machinery spaces on vessels like destroyers.

If we recall the nature of hull damage, we must, therefore, conclude that such damage is always a potential danger to all types

of vessels. However, this danger may be partially overcome and the effects of hull damage may be reduced or eliminated by the proper operation of the hull. Such control of hull damage involves systematic and thorough preparation of the hull for war and battle conditions and efficient, expeditious execution of the plan of control evolved. Let us now consider the principles involved in a systematic plan whereby the effects of hull damage will not be left as a matter of chance but will be reduced to a minimum by the control of the damage.

11-2. Objectives of damage control.

The control of hull damage is based on two objectives. First, the procedure must be such that the vessel may continue on her mission and operate with full effectiveness or with a maximum percentage of her normal efficiency. Second, if this primary objective is unattainable, then damage control must be directed toward the second objective, namely, the vessel must be kept afloat and gotten back to port or to a position where outside assistance is available.

The maintenance of the vessel's offensive power is the first objective of damage control not because it is always more important than getting her back to port but rather because it generally embraces this latter objective. It is impossible to evaluate the relative importance of the two objectives but, under usual conditions, if damage control is successful in preserving the fighting power of a vessel she will also be preserved against loss. If the damage is such that she cannot continue in action, then of course the problem of getting her back to safety is the only consideration. The relative importance of the two objectives depends largely on the type of vessel. On a battleship whose continuation in action as an effective part of the battle line is imperative and which is provided with adequate protection and compartmentation, the whole procedure for damage control must be organized for the purpose of maintaining her offensive power. On an auxiliary which is not provided with adequate protection against hull damage and whose continued operation at any particular instant is not of primary importance, damage control must and should be directed entirely toward getting her back to port in damaged condition. On types of vessels intermediate both in construction and duties between the battleship and an auxiliary, the procedure for damage control is similarly intermediate; but **in all type of vessels damage control is a necessary part of the operating plan and a systematic procedure for its accomplishment must be developed and followed.**

11-3. Phases of damage control.

The minimizing of the effects of hull damage is accomplished in four phases as follows:

(1) Maintenance of water-tight integrity.
(2) Establishing war-time cruising condition.
(3) Conditioning for action.
(4) Counter-measures after damage is sustained.

Each of these phases is an integral part of the control of hull damage; with one neglected or improperly provided for, the value of the other three is materially lessened or entirely lost. The first three, the preparatory measures, are of a routine nature which is not as impressive as the corrective measures after damage; but in no activity is it more true that "an ounce of prevention is worth a pound of cure" than in damage control. The ounce of prevention which insures that a water-tight bulkhead does not leak is easily worth the pound of cure involved in stopping a leak once a compartment is flooded.

Section B—Maintenance of Water-tight Integrity

11-4. General.

The first phase of damage control is the procedure whereby it is insured that the structure and appurtenances of the hull are at all times in effective condition. Since protective devices are not ordinarily subject to deterioration, this phase of damage control chiefly involves the maintenance of the water-tight integrity of the hull subdivision. The hull is designed so that flooding will be restricted to as small an area as possible. The subdivision is carefully inspected and tested when a vessel is built, to insure that boundaries are tight. This quality of tightness is perhaps the most delicate as well as one of the most important qualities of the hull. Water-tight integrity can only be insured by constant and carefully conducted inspections or tests.

11-5. Loss of water-tight integrity.

A water-tight boundary will in time become defective unless its integrity is definitely preserved. The loss of water-tightness may be caused by

(a) The structure may deteriorate; that is, the plating may corrode, the calking may work open, or welding may open up.

(b) The permanent fittings, such as stuffing boxes, bulkhead castings, etc., may deteriorate.

(c) Water-tight doors, hatches, vent covers, etc., may deteriorate or be misused so they do not close properly.

(d) There is a continuous amount of repair and alteration work which involves making holes through water-tight boundaries—the removal of pipes and cables, installation of new fittings, etc. This work is performed for some purpose not related to water-tight integrity and the natural tendency is to complete the work for the purpose intended without thought as to its effect on the water-tightness of the bulkhead or deck involved.

11-6. Periodic tests and inspections.

Because of the above-noted factors, no boundary can be assumed to remain water-tight; rather it may safely be assumed that it will in time lose its water-tightness. The only way to insure that the integrity of water-tight boundaries is maintained is by constant periodic tests and inspections. This periodic determination may be made by

(a) Air tests.
(b) Visual inspections of boundaries.
(c) Leakage inspections.
(d) Check off of boundary fittings.

11-7. Periodic air tests.

If a compartment is filled with a liquid, the water-tightness of its boundaries may be determined. However, excepting fuel oil, water, and gasoline tanks, the filling of any compartment involves a great deal of time and effort and the filling of most compartments of a vessel in service is impracticable because of the damage to the permanent equipment installed in it.

In lieu of filling the compartment with water it may, however, be filled with air under pressure and the water-tightness of its boundaries determined by inspection for air leakage or by observation of the drop in initial pressure with the air supply cut off. Such a test accurately determines the condition of the boundaries and is the only means whereby exact determination can be made on an operating vessel. Provision is made whereby air from the ship's lines can be used to establish a predetermined pressure in the compartment, the supply is then closed off and the amount which the pressure drops in a given interval of time is noted. This air pressure will leak through very small openings which would permit no appreciable leakage of water. Hence, a compartment which is water-tight may show a pressure drop under air test. Such a drop, i.e., the drop in air pressure corresponding to satisfactory water-tightness, is determined for each compartment and is known as the "allowable drop." By comparing this allowable drop with the observed drop, the degree of tightness is ascertained. If it is unsatisfactory, examination of the boundaries is made to determine the cause of the leakage.

In making an air test, extreme care should be taken to insure that the pressure used is no greater than that specified, in order that the boundaries may not be overloaded. Tests should never be made before the proper pressure has been determined by competent authority.

11-8. Leakage inspection.

The tightness of any boundary of a tank containing fuel oil, water, or gasoline may be determined by observing leakage or evidence of leakage on the outboard side of the boundary. Ordinarily, the boundary between adjacent tanks cannot be so inspected and deterioration of such a boundary is improbable. Hence, leakage inspection is generally made on outside boundaries, i.e., boundaries separating tanks from dry compartments. To be satisfactory, such an inspection should be made when the tank is filled to capacity or shortly thereafter, when the stains resulting from leakage are still in evidence.

11-9. Periodic visual inspection.

Certain compartments, such as engine-rooms, cannot be put under air pressure because they are permanently open to the topside.

The tightness of boundaries of such compartments can only be ascertained by visual inspection. This should be accomplished by intensely lighting the compartment on one side of the boundary and darkening the compartment on the opposite side. Observation from the darkened side will reveal any defects which are permeable to light. This inspection should be supplemented by the fitting check-off list described below, to determine defects in fittings which are not of such a nature as to permit the passage of light.

Such visual inspection, unless very carefully conducted, will be of little value and even a careful visual inspection may fail to disclose all the defects. In most cases the boundaries involved are among the most important in the ship, for example, the bulkhead between two engine-rooms. The more effective air test would be used if it were possible. Hence, the visual inspection must be made with extreme care and thoroughness.

11-10. Compartment fitting check-off list.

A further determination of the status of water-tight integrity can be made by inspection of fittings such as doors, hatches, manholes, stuffing boxes, pipe fittings, drain valves, voice tubes, vent ducts, etc., fitted to or piercing a boundary. To make satisfactorily such an inspection, all such fittings in each boundary should be listed in a check-off list, each fitting carefully examined and the results of the inspection noted on the check-off list.

Gasketed fittings, such as doors, hatches, and vent covers, may be subjected to the chalk test. The knife-edge is carefully covered with chalk and the opening closed. A complete chalk mark should be made on the gasket. Any part of the gasket not so marked was not brought into contact with the knife-edge.

The inspection should also include a careful examination of the dogs, gaskets, and hinges. It should be determined that all dogs bear properly and exert an even pressure on the cover plate. Improper packing around the dog shanks should be determined by evidence of looseness or binding. The condition of gaskets, particularly rubber gaskets, should be observed. The gasket should be held properly in place and the rubber should be live and resilient. Rubber gaskets should never be painted or treated with any preparation, since this deadens and rots the rubber.

Inspection of stuffing boxes in bulkhead fittings should be made to insure that the packing is in place and that the fitting is the correct size for the pipe or cable run through it. Particular attention should be paid to stuffing boxes around electric cable, since even under the best conditions they may permit minor leakage.

Such a check off of compartment fittings generally should be made on all compartments, but particularly the fittings in boundaries subjected to visual inspection and not air tested should be very carefully inspected when the visual inspection is made.

11-11. Inspection procedure.

The procedure and general requirements for the conduct of periodic tests and inspections are given in the Bureau of Construction and Repair Manual. The present requirements are that a periodic air test of each compartment to be so tested must be made at least once every 18 months; visual inspections must be made once every 6 months; and leakage inspections, once every 3 months. The results of these inspections and tests are reported to the Bureau, where a continuous record is maintained and steps taken to insure that corrections beyond the capacity of the ship's force are effected during overhaul at the yard.

Combatant vessels are furnished either with a "Schedule of Water-tight Inspections and Tests" or with a "Periodic Air Test Schedule." The former lists all compartments on the ship and specifies the kind of test or inspection to be made on each compartment. Where an air test is specified, the pressure to be used and the allowable drop are given. The latter form of schedule gives only the information for compartments to be air tested, the determination of the extent of visual and leakage inspections being left to the commanding officer.

Generally, air testing is not required on non-combatant vessels such as auxiliaries. Some such vessels are furnished with a schedule of visual and leakage inspections required. On others the extent of the inspections is left to the discretion of the commanding officer.

Section C—Establishing War-time Cruising Condition

11-12. General.

The second phase of damage control involves the steps necessary to put the hull in such a condition that the hazards of war-time cruising will be minimized and conditioning for battle may be expeditiously accomplished. It should be clearly understood that these steps do not include correction of defects in the material condition. Such work is included in the routine operation of the vessel and she must be in satisfactory material condition not only on the eve of battle but on the outbreak of hostilities; that is, the material condition must be satisfactory at all times, in peace or in war.

However, a hull in satisfactory material condition may not be ready for battle or even safe against the hazards of war-time cruising. The peace-time operation of the ship, involving as it does the training and housing of the crew, can best be accomplished under conditions which cannot be considered safe in war time. Therefore, there arises the necessity for putting the hull in war-time cruising condition immediately upon the outbreak of war (or before starting a cruise) and further conditioning just prior to entering battle.

11-13. Conditioning for war-time cruising.

On the commencement of war operations, hazards from mine, bombing, or isolated attacks may arise, in which case the hull should immediately be put in such a condition as to resist these dangers. Also, there are many steps necessary to prepare the hull for battle which can be best accomplished in port or which involve too much time to be deferred until battle is imminent. Finally, there is so much last minute work necessary to prepare the hull for action that as much as possible should be done before setting out on a war-time mission. For these reasons, it is essential that a definite conditioning of the hull be accomplished when a cruise under war conditions is probable. The nature and extent of this conditioning varies with different types of vessels and different situations but generally the reasons above given define the objectives to be attained; that is, the hull should be made as secure as possible against isolated attack, all work involving considerable time should be accomplished, and the vessel should be brought to as near battle condition as the prospective cruising requirements will permit.

11-14. Disposition of equipment.

The first step in conditioning the hull for war-time cruising involves the disposal of equipment useful in peace time but unnecessary or hazardous in war time. Such equipment should be disposed of for the following reasons: First, the minimum draft attainable should be assured; second, much of the equipment constitutes a fire hazard; third, equipment may be in the way and interfere with battle operations.

The extent to which a vessel is stripped at the outbreak of war varies for different types and situations but, generally, part or all of the following equipment should be landed:

(1) Boats and their equipment.

(2) Combustible materials, such as awnings, furniture (except those items essential to reasonable comfort), wood shelving, cases, etc., spare mess tables, manila lines, spare bunting, correspondence files, etc.

(3) Wood decks may be removed.

(4) Stanchions, ladders, spare parts not essential in battle, metal furniture.

Some equipment cannot be disposed of but may be re-stowed so as better to serve its purpose or constitute a lesser hazard in war time. In particular, combustible material which must be kept aboard should be stowed in the most protected places or where it may be wet down or quickly thrown overboard.

11-15. Conditioning of protective devices.

It has been noted that the effectiveness of the protective layer is dependent upon certain spaces within it being filled and others empty. While this condition should always exist, it is essential that it be checked before beginning a war-time cruise. The condition of the voids will seldom be involved, since they will rarely be filled. The oil tanks will generally all be filled when the vessel is fueled and emptied as the oil is consumed during the cruise. The fuel should be taken from the tanks according to an established sequence such that maximum effectiveness will at all times be maintained with the fuel on hand.

11-16. Closure devices.

If water-tight integrity has been properly maintained, the conditioning of the hull compartmentation for war-time cruising will involve only the proper setting (generally closing) of such closure devices as water-tight doors, hatches, manholes, vent covers, drain valves, etc. The procedure may be classified as follows:

(a) Certain openings may be closed at all times except when the compartment involved is entered. Doors, hatches, and vent ducts to storerooms, manholes to double bottoms, and access to hold spaces generally fall in this class. As a matter of training and good seamanship, such spaces should be closed at all times in peace time as well as in war time. If this practice has been established, no conditioning should be necessary for such spaces other than a routine check of the openings.

(b) Certain compartments may be closed outside of working hours. Workshops, issue rooms, plotting room, etc., fall in this class. The securing of openings to such spaces should likewise be a routine practice under all conditions.

(c) Some openings are installed for comfort or ease of operation. For example, many living spaces have more than one hatch or door and ventilation is provided compartments which can be utilized without the ventilation provided. Such openings may be normally open in peace time but should be secured when conditioning the hull for war-time cruising.

(d) Certain openings cannot be secured for prolonged periods. Machinery room and boiler-room hatches, certain doors to living spaces, and many vent ducts fall in this class. Provision should be made, however, for keeping these openings closed as much as possible, or at least for closing them in case the necessity for their closure arises.

Section D—Conditioning the Hull for Action

11-17. General.

The preparation of the battery for action is a definite step easily recognizable. The conditioning of the hull for action is equally important but, since the hull functions at all times, the necessity for preparing it especially for its battle function is not always apparent. Nevertheless, the hull can no more be properly operated without being prepared for action that can the main battery. As in the case of the battery, this preparation does not involve making corrections to defective or neglected material; the conditioning of the hull for action must be predicated on a satisfactory material condition just as, in preparing a battery for action, it is assumed that the guns and ammunition are not defective.

It has been pointed out that certain conditioning can and should be accomplished before a war-time cruise is undertaken. It has been noted that one of the reasons for this conditioning is to make the hull as nearly as possible ready for action at all times. However, certain preparations cannot be effected until immediately before going into action. Unless a systematic procedure is developed for conditioning the hull for action, it probably cannot be accomplished in the time available, and satisfactory accomplishment in an unlimited time is highly improbable.

11-18. Objectives of conditioning for action.

The objectives of conditioning for action are the elimination of or minimizing the effects of hull damage and provision of means for expeditiously neutralizing, so far as possible, the effects which may result from damage incurred. These objectives involve the following factors:

(a) Draft, stability, and trim.
(b) Protective devices.
(c) Water-tight subdivision.
(d) Gas protection.
(e) Fire protection.
(f) Preparation for counter-measures.

11-19. Draft, stability, and trim.

The hull characteristics, draft, stability, and trim are, as noted in Chapter VIII, seriously affected by hull damage. Each of these characteristics is fairly definitely fixed by external conditions and by the relation between it and the other two characteristics. However, there is some variation of each characteristic possible in preparing for action, and each characteristic should be checked before going into battle and measures taken to establish it as near as possible to the most desirable value.

(a) *Draft.* In considering the draft at which a vessel should go into action the following factors must be considered:

First, the draft will largely depend on the scene of action; that is, how much cruising has been done since the vessel was last refueled and resupplied.

Second, the draft determines the amount of reserve buoyancy and the position of the protection relative to the waterline. The less the draft, the more the reserve buoyancy, but too shallow a draft may bring the armor too far out of the water. On the other hand, a deep draft will reduce the reserve buoyancy and bring the armor too deep in the water.

Third, a vessel's average draft increases as she grows older. Alterations and changes generally involve added weights and a vessel tends to draw more water than she is designed for.

The draft should be as near as possible to the designer's draft for battle condition. Too deep draft may sometimes be avoided by taking on a limited supply of fuel or, in extreme cases, fuel may be pumped overboard. Too shallow a draft may be more easily corrected by filling empty fuel tanks with water.

(b) *Stability.* In considering the stability of a vessel when going into action, there are two conflicting requirements. First, the stability should be as large as possible to allow for loss due to hull damage. Second, too much stability makes the vessel stiff and a poor platform for a battery or other battle operations. Generally, however, the former consideration is predominant and the stability should accordingly be as large as possible under the existing conditions.

The draft determination also partly determines the range of stability, since it determines the freeboard and thus the angle at which the deck edge goes under. So far as the draft determination also involves the disposition of weights, it effects the initial stability, that is, the metacentric height. However, a considerable influence on initial stability can be effected by the determination of free surface. For maximum stability, tanks with large transverse dimensions should be either empty or completely filled, and consumption of both fuel and water should be so planned that partly filled tanks are at all times kept to the minimum.

Since the consumption of fuel, water, and stores involves the reduction of weights well down in the ship, the maintenance of proper stability becomes increasingly difficult as the cruising distance increases. Further, the expenditure of ammunition also raises the center of gravity and the stability condition accordingly becomes less satisfactory as the battle progresses. These efforts may be counteracted by flooding empty fuel or water tanks. This procedure must of course be determined with consideration to the resultant increase of draft.

(c) *Trim.* The determination of the trim of a vessel entering battle is generally a simple problem and the necessary steps are usually easily executed. The vessel should enter battle on an even keel (no list) and trimmed fore and aft to the designer's waterline. In case the action takes place with the full or nearly the full amount of fuel and supplies, the attendant fore-and-aft trim must be accepted; but, generally, fore-and-aft fuel distribution can be accomplished to effect the desired trim.

11-20. Protective devices.

If the protective layer is conditioned for a war-time cruise, as noted in *Art. 11-15*, further conditioning for battle will not be necessary or practicable, except that in the determination of the draft it may be necessary to flood certain fuel tanks in the protective layer. In extreme cases, it may be desirable to pump some of the oil overboard to decrease the draft. In either procedure it must be assured that the distribution of the oil and water is such as to give maximum efficiency of the protective layer.

11-21. Water-tight subdivision.

A definite conditioning of the subdivision is accomplished before starting a war-time cruise. However, this condition is not satisfactory as a battle condition for the following reasons:

First, in preparing for action, control of damage is the paramount consideration. A standard of conditioning must be effected which involves interruptions not acceptable when cruising but absolutely imperative in battle.

Second, many openings which must be continuously or intermittently opened under cruising conditions may be closed for the duration of the battle.

Third, some openings which may be closed during cruising condition must be opened in battle.

11-22. Battle access.

Generally, the operation of the ship in battle is based on the personnel remaining in fixed battle stations and the movement of material, particularly ammunition, from one station to another. This permits the closure of such access openings as hatches leading to boiler-rooms and engine-rooms, doors to living spaces and battle stations (such as control station and plotting room) to be closed as soon as the battle stations are manned. On the other hand, magazine doors and ammunition passing scuttles, normally closed, must be opened in battle.

11-23. Ventilation in battle.

Much of the ventilation necessary even in war-time cruising condition can be closed down in battle. All ventilation to living spaces, magazines, and such spaces as the steering gear room, control stations, battle dressing stations, etc., falls in this class. On the other hand, the satisfactory operation of certain ventilation systems is most important in battle. The forced draft system to the boiler-rooms, the ventilation of machinery spaces and closed battle stations wherein a large number of men are stationed must be maintained and the conditioning must be planned so that utmost reliability of such systems with minimum interference with subdivision is attained.

11-24. Gas protection.

The protection given the personnel against war gases is not truly a phase of the control of hull damage but the conditioning of the hull for battle also provides protection against gas. The closure of water-tight doors and hatches, the shutting down of ventilation blowers, and the fitting of vent duct covers prevent the spread of gas as well as the spread of flooding. There are, however, many battle stations in the upper part of the vessel, such as the conning tower, director stations, fire control stations, etc., which are sometimes closed solely for the purpose of protecting the personnel against gas attack.

11-25. Fire protection.

Fire resultant from hull damage, particularly that caused by shell or bomb explosions above water, must be given serious consideration in preparing a vessel for battle, not only because of the probability of fire but also because the usual means for combating it are not operative in battle. Access to the various parts of the ship is, as has been noted, totally or partially interrupted by the closure of doors and hatches; the personnel usually available for fighting fire are engaged in their various battle duties; and the normal supply of water is interrupted. It is essential that flooding of spaces from ruptured water lines be prevented. Hence, an important consideration in preparing a vessel for action is the conditioning of the fire mains. All risers and lines above the under-water body are particularly susceptible to damage and should accordingly be closed before going into action. On the other hand, in case of fire the provision of water through such lines is necessary. Generally, all risers and branches from the fire main are closed at the root valves before going into action. In case of fire these valves are opened as necessary and practicable to supply water.

It can readily be seen that fire protection in battle must be, as much as possible, fire prevention. Hence, the extreme importance of removing all combustible materials, particularly from the topside, before starting a war-time cruise.

11-26. Preparation for counter-measures.

The successful accomplishment of measures to counteract the effects of hull damage in battle is largely dependent upon the preparations for such action before the battle begins. The preparatory steps involved will be discussed in the following sections in connection with the treatment of the counter-measures. It should be noted at this time that these preparatory steps are an important phase of conditioning the hull for action.

Section E—Counter-measures on Battleships

11-27. General.

The phases of damage control already discussed are preventive; the plans are based on the probability of various degrees and forms of hull damage; and the procedures are determined with a view to minimizing the effects of any damage which may be incurred. Such preventive measures are essential and damage control can never be

effective, except by chance, unless they are properly carried out. However, these preventive measures cannot be relied upon to preclude serious effects of hull damage. Let us now consider how such effects may be neutralized or minimized by counter-measures which may be taken after any particular hull damage has been sustained. These counter-measures may be classified as,

(a) Establishing a flooding boundary around the damaged area.
(b) Counteracting the effects of flooding.
(c) Strengthening weakened structural members.
(d) Fire fighting.
(e) Clearing away wreckage and debris.
(f) Neutralizing war gas.

The situations, the relative importance of factors, the objectives, and the means at hand for their accomplishment are widely different for the different classes of vessels. The present discussion will refer to battleships (and aircraft carriers so far as they conform to the battleship type) and the succeeding section will deal with other types of vessels.

11-28. The counter-measure problem.

The objective of counter-measures on a battleship is fundamentally the maintenance of the vessel as an effective unit in the battle line. The considerations are:

(a) Time is the important element. Counter-measures, to be effective, must be accomplished immediately after the damage is sustained.

(b) The counter-measures must be directed toward keeping the vessel operative for the probable duration of the battle; her final preservation must be accomplished if possible but not at the expense of removing her from the battle line as long as any part of her offensive power can be maintained.

(c) The vessel must be put on an even keel, or nearly so, and the trim must be reduced to a point consistent with maintenance of battle speed.

(d) Stability must not be reduced by the counter-measures to a point where the vessel is unseaworthy in the seaway obtaining at the time or likely to be encountered.

(e) Damage interfering with the operation of the battery or machinery must be corrected so far as possible.

11-29. Assumptions.

The hull damage which may be sustained varies over so wide a range that it is impossible to consider, or even foresee, all of the situations which may develop. However, as a basis for discussion, the following assumptions will be accepted as illustrative, if not typical:

(a) The vessel will be capable of continued action after one major under-water explosion and of returning to port after two such explosions, provided they do not occur in the same area.

(b) The list produced by one under-water explosion will not exceed about 20° and the change of trim will not exceed that which will bring her weather deck awash at the bow or at the stern.

(c) Not more than 25 per cent of the reserve buoyancy will be destroyed by a single damage.

(d) No single damage will dangerously weaken the hull girder but local weakening of bulkheads and decks will occur.

(e) Not more than 50 per cent of the main propelling machinery or boilers will be put out of commission.

(f) No projectile will penetrate the side armor and explode inside the armored box.

(g) No aërial bomb will penetrate the ballistic decks and explode below the armored box.

(h) The steering engine and gear may be damaged but not made permanently inoperative.

(i) No explosion of ammunition in magazines will result from any form of damage.

(j) Topside damage will result in carrying away one mast and all topside gear in its vicinity.

(k) The above damage may result in debris and wreckage which will foul all the turrets in the forward or in the after group.

(l) No effective gas attack will be incurred during the active phase of a major engagement.

11-30. Typical counter-measure requirements.

Based on the above assumptions, counter-measures must be such as to accomplish the following:

(a) Right a list of about 20° and simultaneously correct a trim of two deck heights by the head or one deck height by the stern without a dangerous reduction of freeboard or initial stability, in a sufficiently short period of time that the ship's battery can be brought on the enemy before the aspect of the battle has changed. This means that, within a period of about ten minutes, the list must be reduced to about 2° and the trim reduced to less than one deck height, with an accompanying additional loss of not more than 25 per cent of reserve buoyancy or initial stability.

(b) Re-enforce weakened bulkheads and decks before they give way under water pressure or shock or, in the case of machinery bulkheads, before they are sufficiently distorted to cause flooding beyond the capacity of the pumping facilities.

(c) Make adjustments and minor repairs, or fit jury rigs, to the steering engine and gear in a sufficiently short time to permit the ship to regain her position in the battle line.

(d) Put out fires on the topside before they spread to ammunition supply or get beyond control.

(e) Clear away wreckage and debris on topside from turrets and main battery control and ship control stations.

(f) Take effective steps toward neutralizing gas attack.

11-31. Establishing the flooding boundary.

Immediately after hull damage involving flooding is incurred, it is essential that a definite boundary to the flooding be established. This involves:

(a) The determination as to what compartments are flooded or are being flooded as a direct result of the damage.

(b) An inspection of all compartments adjacent to those classified under (a) to ascertain sources of leakage into these adjacent compartments. Such leakage may be due to distortion of the watertight boundaries, to doors or hatches being sprung, or to bulkheads and decks being subjected to pressures greater than they can stand.

(c) A decision must be made as to which of these adjacent compartments can be kept dry and which are leaking at such a rate that their flooding cannot be prevented.

(d) Immediate steps must be taken to stop or reduce leaks into compartments which are to be saved and to put available pumping facilities into compartments where leakage cannot be entirely prevented or stopped.

By this means the leakage will be definitely limited to the smallest possible number of compartments; a definite flooding boundary will be established. This is highly important for, in most cases of hull damage, boundaries near the explosion not actually demolished are badly distorted. Such boundaries will prevent initial flooding but, unless steps are taken to prevent it, subsequent slow and moderate leakage will result in the gradual flooding of a number of compartments not originally flooded, which flooding could be prevented. Unless a definite flooding boundary is established as close to the damaged area as conditions permit, initial flooding not of dangerous proportions may slowly spread to such an extent as to cause the loss of the ship.

11-32. Counteracting effects of flooding.

The correction of flooding effects may be accomplished by:
(a) Removal of flooding water.
(b) Shifting weights.
(c) Counter-flooding.

(a) Removal of the flooding water restores the ship to her initial condition of draft, stability, and trim. This is accordingly the most desirable method; however, it is seldom possible. In rare cases the flooding may be restricted and the water pumped out as fast as it comes in. However, the rate of flooding through a hole only a few inches in area generally exceeds the capacity of any pumps installed. Also, in some cases, the damage may be located near or in the bottom of a compartment and an air pressure can be put on the compartment to force out the water. This method is effective, however, only in keeping the water down to the level of the top of the damage. Further, it requires absolute tightness of the upper part of the compartment to prevent the leakage of air faster than it can be introduced; and the air pressure necessary to force out the water must exceed the water pressure due to the external head. This is sometimes greater than the weakened structure of the compartment will stand.

We must accordingly conclude that, although removal of the flooding water is the most desirable means of counteracting flooding effects, it cannot be relied upon as a practicable means except in rare instances.

(b) Correction of list and trim may be effected by shifting weights on board. Although this may be accomplished by shifting any weight, the only practicable means available is the shifting of fuel oil and, to a less extent, fresh water. The amount of correction possible is limited by the location of the tanks and the amount of fuel and water on board at the time of damage. The speed with which correction may be effected is limited by the pumping capacity. This is generally too low to effect large corrections in the time available. However, shifting oil and water neither increases the vessel's mean draft nor interrupts the usual operation of the ship. It is accordingly resorted to wherever the desired correction can be accomplished within the time available.

Other weights, particularly ammunition, may sometimes be shifted to correct list and trim. Since this presupposes some empty magazines and since the magazines are generally near the center line (with a correspondingly small effect), this procedure is not generally relied upon but may be effective under some conditions.

(c) Counter-flooding is the generally accepted method of counteracting flooding effect. This consists in filling a compartment or compartments on the side of the ship opposite the damaged area and located sufficiently forward or aft to correct trim. For example, if the flooding is aft on the starboard side, the proper sized compartment forward on the port side is counter-flooded.

Counter-flooding has the following disadvantages:

(1) It results in further increase in draft, with consequent loss of freeboard and reserve buoyancy. This reduces the ship's efficiency, as noted in Chapter VIII.

(2) It does not correct the loss of stability due to free surface effect and may even increase this loss.

(3) The spaces usually available for counter-flooding are voids upon which the effectiveness of the protective layer against subsequent under-water explosion may depend.

Counter-flooding is accordingly resorted to only when the correction of list or trim is considered more important than the increased draft, loss of under-water protection, and possible additional loss of stability.

11-33. Methods of counter-flooding.

Counter-flooding may be accomplished by:
(a) Equalizing pipes.
(b) Counter-flooding valves.
(c) From the fire main.

(a) Equalizing pipes are large pipes run between two similar compartments on opposite sides of the ship. If the compartment on either side is damaged, both compartments are flooded. The chief disadvantage of this system is that, instead of correcting trim, the counter-flooding actually increases it, since the counter-flooded space is at the same end of the ship as the flooded space.

(b) Counter-flooding valves are large valves fitted in the shell plating near the bottom of the compartments, generally, the outer voids. These valves are operated from a control station or from the third deck. They permit simultaneous correction of list and trim.

Counter-flooding valves give a high rate of flooding when first opened but, as the water level in the compartment rises, the rate decreases rapidly due to equalizing the pressure inside with that outside. Hence, counter-flooding valves reduce a large list to a moderate value in a short time but further correction is slow. Counter-flooding valves are most effective if opened immediately when damage is incurred and before the vessel takes a severe list to the damaged side, since this list brings the valves on the opposite side nearer the surface, thus decreasing the effective head of the outside water and reducing the rate of counter-flooding.

Counter-flooding valves have the disadvantage that counter-flooding is definitely limited to the compartments in which valves are fitted.

(c) Counter-flooding through the fire main is generally accomplished by hooking hose to near-by fire plugs and either attaching them to special fittings or dropping them through manholes in the top of the compartment. The rate of counter-flooding is dependent upon the number of hose which can be rigged and is always limited by the capacity of the pumps. Hence, this means of counter-flooding is generally too slow to be satisfactory as a primary means for quickly correcting a large list. It is, however, useful as a secondary

means to counter-flooding valves, since it permits counter-flooding of spaces not fitted with valves.

In all forms of counter-flooding, it is essential that means for venting the compartment be provided; otherwise, an air pressure will be built up which will materially reduce the counter-flooding rate.

11-34. Re-enforcing bulkheads and decks.

Means must be provided for temporarily re-enforcing bulkheads and decks, for two reasons. First, bulkheads and decks near the damaged area may be weakened by the damaging agent. Second, it is impracticable to build all decks and bulkheads to withstand the combination of water pressure and dynamic action to which they may be subjected in case of flooding. As a supplementary step to the limitation of flooding discussed in *Art. 11-31*, all decks and bulkheads in the vicinity of damage should be immediately inspected and re-enforced with shores or other available means, as necessary. Such action may frequently save a boundary from subsequent collapse, with further spread of flooding or decommissioning of equipment. It is particularly important in the case of the large machinery and boiler-room bulkheads, both because of their size and as a precaution against loss of propelling power.

11-35. Other counter-measures.

The special considerations involved in fighting fires incident to hull damage have been discussed in *Art. 11-25*. The clearing away of debris and wreckage involves no general problem other than the provision of the necessary tools such as crowbars, jacks, tackle, axes, gas torches, etc. The problem of clearing a vessel of war gas is of a confidential nature and will not be treated in this discussion.

Section F—Counter-measures on Smaller Vessels

11-36. General.

Smaller vessels such as cruisers and destroyers are, as previously noted, neither adequately protected nor satisfactorily compartmented. It might, therefore, be concluded that attempts to control damage on such vessels are useless; that either no damage of moment will be incurred or if damage is inflicted it will be decisive. In either case, damage control will not influence the result. **Such a conclusion is far from correct.** There is, of course, a range of damage so minor as to require no orderly, planned control. There is also a range of damage so extensive that no control will be effective. But between these two extremes, there is a wide range of damage such that, without damage control, the vessel will be lost; whereas the effects of the same damage may, by a well-planned system of control, be successfully combated and the vessel saved, perhaps even kept in the battle line. **Damage control on smaller vessels, although not as comprehensive, is as important as on battleships.** Maintenance of water-tight integrity, conditioning the hull for war-time cruising, and conditioning for action, the preventive phases previously discussed, apply equally to all vessels. The fourth phase, counter-measures after damage has occurred, requires separate consideration.

11-37. Objectives of counter-measures.

On smaller vessels the primary objective of counter-measures is to keep the vessel afloat and get her back to port. The plan must be made accordingly, although it must always be borne in mind that whenever possible the vessel must be kept in the battle line.

While counter-measures on the smaller vessels are generally similar to those previously discussed on battleships, the difference in the objectives gives rise to two differences. First, time is an important element on smaller vessels in that it influences the effectiveness of the measures taken but is not as vital to the objective as in the case of the battleship. Second, list and trim correction on smaller vessels should be primarily governed by the requirements of safety of the vessel, her immediate operation in the battle line being an important but a secondary consideration.

11-38. Counteracting effects of flooding.

The vessels now under consideration are not provided with a protective layer; also, as previously noted, quick correction of list and trim is not essential; hence, no counter-flooding valves are provided. Correction of list and trim is accordingly accomplished by shifting fuel or by counter-flooding from the fire main. Shifting of fuel oil will generally be more effective than on battleships because of the time element. If counter-flooding is employed, compartments are flooded which will give the desired results, with the least interference with the operation of the vessel.

11-39. Strengthening weakened structural members.

On lightly constructed vessels, damage may not only weaken the structure locally but also may seriously reduce the longitudinal strength of the hull. Although such a condition may frequently be beyond control, it should be kept in mind and a careful examination made after damage is incurred to determine the extent of weakening and possible means for temporarily strengthening the weakened members.

Section G—Damage Control Procedure

11-40. Cognizance.

The provision of material and equipment and the design and construction of the hull with respect to the control of damage are under the cognizance of the Bureau of Construction and Repair.

The maintenance of the hull and the operations involved in damage control are the responsibility of the commanding officer. The organization and direction of damage control are the primary duty of the damage control officer. However, it is apparent from the previous discussions that, perhaps more than in any other phase of battle efficiency, the interest, assistance, and co-operation of all hands is essential to the success of damage control. In particular, the maintenance of water-tight integrity requires the active assistance of every officer on the ship. No damage control organization can correct defects in water-tight integrity as fast as they are made by the rest of the crew if attention to this question is not general throughout the ship. Also, the preparatory steps for cruising and battle effected by closing doors, hatches, vent ducts, etc., may be partly or entirely nullified unless all personnel appreciate the reasons for the openings being closed. Such closure generally involves discomfort; frequently it involves hardship. Unless a hearty respect for closed openings in war time is instilled in every member of the crew, no procedure for closing them will insure that they will be closed when damage is incurred; and, unless the engineer force works very closely with the damage control officer, effective shifting of fuel oil and counter-flooding may be impossible.

Damage control is an all-hands problem.

11-41. "Damage Control Book."

The Bureau of Construction and Repair has initiated the preparation of a *Damage Control Book* for combatant vessels. In this book are given the data and plans necessary for the operating personnel to effect an organization and procedure for the control of hull damage. A vessel's *Damage Control Book* should be studied and consulted in the application of the principles discussed in this and the three preceding chapters and for details of her construction and installation involved in her particular damage control problem and procedure.

In other words b moves about m, i.e., the liquid in the tank acts as if it were a weight suspended from m. The effect of the free surface, then, is to produce a **virtual** rise of the center of gravity of the liquid from b to m. This change in the location of the center of gravity of v produces a change in the location of G. It moves from G to G_1 where

$$W \times GG_1 = w \times bm$$

$$= \frac{v\delta}{36} \times bm$$

$$\text{And } GG_1 = \frac{v\delta \times bm}{36W} = \frac{v}{V} \times \frac{35\delta}{36} bm$$

$$= \frac{35\delta}{36} \times \frac{v}{V} \times \frac{i}{v} = \frac{35\delta}{36} \frac{i}{V}$$

$$\therefore G_1M = GM - GG_1$$

$$= GM - \frac{35\delta}{36} \frac{i}{V}$$

That is, the effect of the liquid having a free surface is to reduce the transverse metacentric height by an amount equal to $\frac{35\delta}{36} \frac{i}{V}$. If this liquid is sea water this value reduces to $\frac{i}{V}$.

It should be noted that only the moment of inertia of its free surface and not the amount of liquid in the tank affects the loss of GM. This is because the volume of liquid added to the low side does not depend upon the amount of liquid in the tank but only on the angle of inclination. That is, the upsetting moment produced by the liquid running down hill is independent of the amount of liquid in the tank. While we employ the moment of inertia of the free surface of the liquid to obtain the reduction of GM, it should be remembered that it is purely a mathematical conception, not a physical entity; the reason that liquid having a free surface reduces the initial stability is because it changes shape, thereby producing a moment which tends to capsize the ship.

It is impossible to avoid free surface in some tanks. The effect of this free surface is reduced by fitting longitudinal bulkheads.

Since i varies as the cube of the half breadth, it follows that if the tank in Fig. 26 is divided in two parts by a longitudinal water-tight bulkhead, the reduction in GM due to a free surface in one of these two tanks will be only **one eighth** the reduction without this bulkhead. And if there is a free surface in both, the reduction of GM is **one-fourth** of what it would be were they in one tank.

Section E—Effects of Flooding

3-22. General.

Flooding of a part of a hull which is normally dry may be considered as an addition of weight, or it may be thought of as the loss of the buoyancy normally possessed by the flooded spaces. These two conceptions give rise to two mathematical treatments of the problem—the "added weight method" and the "lost buoyancy method."

The mathematical problems involved in either method are too varied in nature and depend too much on experience and judgment as to permissible assumptions to permit of any generalization useful to the layman. These mathematical problems will not, accordingly, be discussed; the physical conceptions will be presented and statements of certain basic formulas will be given. These physical conceptions, as well as the mathematical solution of actual problems, are differentiated by three different conditions of flooding as follows:

(a) Flooded compartments are completely filled.
(b) Flooded compartments are partially filled and not in communication with the sea.
(c) Flooded compartments are partially filled and are in free communication with the sea.

3-23. Permeability.

Before proceeding further into the discussion of flooding, it will be well to introduce the factor of permeability, designated by symbol "p." Many compartments in a ship contain some solid matter. If such compartments are flooded, the weight of the water admitted, or the volume of the buoyancy lost, depends upon the percentage of the volume of the compartment which is occupied when the flooding begins. The term permeability has been adopted by naval architects to express the ratio between the volume of water that may actually enter a compartment and the gross volume up to the flooding level. The difference between these volumes is the space occupied by machinery, stores, structural parts or other objects in the compartment. According to Hovgaard the permeability of engine-rooms will rarely exceed 0.70; boiler-rooms, 0.75. The average values of permeability of magazines and storerooms is 0.65; of living spaces, 0.90. If a compartment is partially filled with a liquid other than sea water, the volume of this liquid must be deducted from the total volume to the level of flooding to determine the increase in displacement, or lost buoyancy, due to flooding. From the foregoing, it is apparent that there may be an appreciable difference between the volume of a compartment and the volume of sea water that may be admitted in flooding.

In the following discussion, permeability is assumed as 1.0 in order that the factors under discussion may not appear involved. Allowance for a permeability of less than unity may be made by simply multiplying the volume (or weight) of flooding water by the permeability value.

3-24. Effects on initial stability of flooding; Compartment completely filled.

If the flooded compartment is completely filled, there is no free surface; that is, the flooded water is confined to a fixed shape and distribution the same as a solid substance. The effects on the increase in draft; the shift in the position of the ship's center of gravity, center of buoyancy and metacenter, and change of trim may all be determined by applications of the formulas and methods applicable to the consideration of an added weight. The previous discussion of the effects of an added weight, illustrated by the two examples in *Art. 3-19*, applies in its entirety to the case of the completely flooded compartment. For moderate cases of flooding the following is a summarization of the discussion and formulas previously deduced:

(*a*) *Increase of mean draft.*

$$\Delta D = \frac{w}{T} \text{ or} \qquad (1)$$

$$\Delta D = \frac{420w}{A} \qquad (2)$$

Where ΔD = increase in mean draft in inches.
- w = weight of flooding water = net volume of flooded compartment (making allowance for permeability) divided by 35.
- T = tons per inch immersion.
- A = area of water plane in sq. ft.

ΔD may also be obtained by entering the displacement curve with the new displacement (W+w) and obtaining corresponding new draft.

For more exact determination of the new draft than obtained by the above methods, the mean between the original and final values of T in formula (1) or the values of A in formula (2) must be used.

(*b*) *Change in initial stability.*

$$G_1M_1 = GM - \Delta G + \Delta M \qquad (3)$$

$$\Delta G = \frac{w \times h}{W+w} \qquad (4)$$

$$\Delta M = \Delta B + \Delta \overline{BM} \qquad (5)$$

Where G_1M_1 = new value of metacentric height.
- GM = value of metacentric height before flooding.
- ΔG = movement of C.G. of ship (positive if up).
- ΔM = movement of metacenter of ship (positive if up).
- ΔB = movement of center of buoyancy of ship (positive if up).
- $\Delta \overline{BM}$ = increase in value of metacentric radius.
- w = weight of flooding water.
- h = vertical distance between C.G. of flooding water and C.G. of ship.
- W = displacement of ship.

The above discussion concerns transverse initial stability. By proper substitution of values and factors, it may also be applied to longitudinal stability, but for most cases change in longitudinal GM is so small, compared to the initial value, that it can safely be neglected.

Since the flooding is due to gravity, the center of gravity of flooding water is below the waterline and in usual ship forms it is below the center of gravity of the ship, that is, ΔG is negative, and being also subtractive it results in an increase in GM. It can be stated as the general rule that complete flooding increases initial stability.

In order that the calculation of the change in the value of GM can be made, the original position of G and the original value of GM must be known and displacement curve must be available to determine new position of M after flooding.

(*c*) *List effect.*

$$\tan\theta = \frac{w \times d}{W \times G_1M_1} \qquad (6)$$

Where θ = angle of list.
w = weight of flooding water.
W = displacement of ship.
G_1M_1 = new value of GM as determined by (*b*) above.
d = horizontal transverse distance between C.G. of flooding water and C.G. of ship.

(*d*) *Change of trim.*

$$\Delta T = \frac{M}{C} \qquad (7)$$

$$M = lw \qquad (8)$$

$$d_f + d_a = \Delta T \qquad (9)$$

$$\frac{d_f}{d_a} = \frac{L - x}{x} \qquad (10)$$

$$C = \frac{W}{12} \text{ (very approximate)} \qquad (11)$$

Where ΔT = change of trim in inches.
M = trimming moment.
C = moment to change trim 1 inch.
l = horizontal fore-and-aft distance between C.G. of flooding water (center of volume of flooded compartment) and C.G. of ship.
w = weight of flooding water.

d_f = change of draft forward.
d_a = change of draft aft.
L = length of waterline.
x = horizontal fore-and-aft distance between after draft marks and center of flotation (C.G. of waterline).

In many cases sufficiently accurate approximate results may be obtained by assuming the center of flotation and the center of gravity to be in the ⊗.

Formula (11) is, as stated, very approximate and is based on the assumption that the longitudinal GM equals the length of the ship. This formula should not be used if the value of C can be determined by reference to the displacement curves.

It may be noted that, as stated in (*b*) above, any change in longitudinal initial stability is neglected in the above formulas.

3-25. Effects on initial stability of partial flooding of a compartment not in free communication with the sea.

Suppose a compartment such as an oil or water tank is partially filled. Then, as the ship changes its position in a seaway the form and distribution, but not the amount, of the fluid changes. This same situation exists when a compartment is partially filled due to damage, and the leakage is stopped before the compartment is completely filled. Further, during the slow flooding of a compartment below the waterline through small leaks, the amount of water does not fluctuate due to the ship's movement in a seaway, as is also the case of a compartment partially above the waterline which has been filled to the mean outside water level through small leaks. Finally, if a compartment completely below the waterline, having a water-tight overhead deck, is flooded due to slow leakage, the flooding water will compress an air bubble in the top of the compartment; that is, a free surface will result without fluctuation of the amount of water due to the ship's movement in a seaway.

Consider the effects of such flooding; that is, partial flooding of a compartment by a fixed, or non-fluctuating amount of water.

If the water in such a partially filled compartment were frozen, the water would have the same effect as if a solid weight of the same size and shape had been placed in the same location. If a very thin layer on top of this frozen water is now supposed to be melted, this layer of water will lose its fixity and will change location as the ship takes a small inclination. If the melted layer is of infinitesimal depth, and the movements of the ship are likewise infinitesimal, the free surface will affect only those stability characteristics which are determined by the vessel in the normal upright position, that is, the initial stability. This free surface of infinitesimal depth will, in other words, affect only the vessel's action when she **starts** to roll or pitch. Once the rolling or pitching action is started, that is, as soon as the value of the inclination becomes finite, the effect of the movement of the flooding water depends upon its depth, but at the **beginning** of the ship's motion, the effect of free surface is independent of depth of water involved; that is, the free surface effect on the initial stability (transverse and longitudinal metacentric heights, values of which, as previously explained, are exactly determinate only for infinitesimal inclination) is independent of the volume of water involved.

It is thus apparent that, when a fixed or non-fluctuating amount of water enters a compartment and does not completely fill it, the effect on initial stability may be conceived as that which would be produced if the water were completely frozen except for an infinitesimally thick layer on top. Such a conception involves the application of the added weight method to mathematical problems involved in such a case of flooding.

It is obvious that the treatment of such problems must be based on determining the effect of the weight of the supposedly frozen body of water and adding to the results so obtained the effect of the infinitesimally thick top layer of free water. The effects of the weight of frozen water are exactly the same as if the same amount of water completely filled the compartment, which effects have been discussed in the previous article. Let us then consider the additional effects of the free surface on the ship's characteristics.

(*a*) *Increase of mean draft.*

The infinitesimal layer of free water can of course have no effect on the mean draft of the vessel. Hence, the effect on draft is the same as that presented in the preceding article.

(*b*) *Initial stability.*

$$G_1M_1 = GM - \Delta G + \Delta M = GM - \Delta G + \Delta B + \Delta\overline{BM} \qquad (12)$$

(from formulas (3) and (5))

$$G_2M_2 = G_1M_1 - \frac{i}{V} \text{ (from } \textit{Art. 3-21}) \qquad (13)$$

$$\therefore \quad G_2M_2 = GM - \Delta G + \Delta B + \Delta\overline{BM} - \frac{i}{V} \qquad (14)$$

Where GM = metacentric height before flooding.

G_1M_1 = metacentric height if flooding water is supposed to be completely frozen.

G_2M_2 = actual metacentric height after flooding.

ΔG = movement of G (positive if up) due to weight effect only.

ΔB = movement of center of buoyancy (positive if up) due to weight effect only.

$\overline{\Delta BM}$ = change in value of BM due to weight effect only.

i = moment of inertia of free surface about its own neutral axis.

V = volume of displacement of ship.

These formulas may be applied to either transverse or longitudinal initial stability but, as in the case of complete flooding, the reduction in longitudinal GM is usually so small compared to its initial value that the change can be safely disregarded.

Formula (14) shows algebraically what has been stated above; that is, that in the case of a partially flooded compartment the change in GM is that due to the weight effect plus that due to the free surface effect. Further, since i/V is always a positive value preceded by a minus sign, the effect of free surface alone is always to reduce the value of GM.

(*c*) *List effect.*

A strictly accurate consideration of list effect must deal with an infinitesimal angle of list, corresponding to the infinitesimally thick layer of free water which has been assumed. However, for practical applications, the error in the case of list up to 10° may safely be disregarded.

$$\tan\theta = \frac{w \times d}{W \times G_2M_2} \qquad (15)$$

Where θ = angle of list.
w = weight of flooding water.
W = displacement of ship.
G_2M_2 = new value of GM, as determined by formula (14).

It will be noted that this formula is the same as formula (3) except for the value of the metacentric height. In other words, for small inclinations (up to about 10°) the list effect due to a partially flooded compartment is sensibly different from that due to a completely flooded compartment only in that the value of GM is less by the amount of i/V, which represents the free surface effect. Since, as above noted, this effect always reduces the value of GM, and since the factor GM appears in the denominator in equation (15), it is thus shown mathematically that free surface always produces more list than that produced by the same amount of flooding without free surface.

(*d*) *Change of trim.*

As previously stated, change in longitudinal metacentric height can, for moderate cases, be neglected. Applying the same reasoning to changes in trim as was applied in (*c*) above, for transverse inclinations; namely, that the inclination in a case of partial flooding differs from that in the case of complete flooding only in that a different value of GM is used, we see that, neglecting the change in GM, the change in trim due to partial flooding is, for moderate values, essentially the same as for a similar amount of complete flooding.

3-26. Effects on initial stability of partial flooding; Compartment in free communication with the sea.

Suppose a compartment is damaged by the opening up of a large hole in the side plating. If the compartment is completely below the waterline and is vented, water will completely fill it and we have the condition of a completely filled compartment previously discussed. If, however, the compartment is only partially below the waterline, water will flow into it up to the height of the external waterline. Further, if the compartment is entirely below the waterline and is not vented, an air bubble will be entrapped above the flooding water, and water will flow into the compartment compressing the entrapped air until the height of water is such that the air pressure inside exactly balances the pressure head of the outside water.

In either of the above two cases of partial flooding a free surface exists and all the effects discussed in the previous article will result. However, this previous discussion was based on a non-fluctuating amount of flooding water. In the present case, if the ship heaves, rolls or pitches more water will enter the compartment or some will run out of it as the ship's motion lowers or raises the compartment relative to the external waterline; that is, the amount of water fluctuates as the ship works in the seaway. Hence, the weight of flooding water continually varies, and calculations based on the conception of a weight having been added to the ship fail.

Consider the damaged compartment partly above the waterline. As the ship rolls towards the damaged side more water enters the compartment; as the ship rolls away from the damaged side water leaves the compartment, keeping the water level in the compartment always the same as the level of the external waterline.

Suppose now that the ship had been so built that the compartment supposed to be damaged had been excluded from the ship's form; in other words, consider that the space occupied by the compartment had been left without any external plating. Such a conception can be visualized in the center line well of a sailing vessel fitted with centerboard. With this conception it is clear that the space involved is not a part of the ship; that is, it is a part of the sea within the outer confines of the hull. As such, it contributes nothing to the ship's buoyancy or stability characteristics. Whether the space is so conditioned by design or damage is of no moment. Hence, we may conceive a partially flooded compartment in open communication with the sea as having been removed from the ship's hull so far as buoyancy and stability are concerned. Upon this conception the lost buoyancy method of computations is based. If the partially flooded compartment is entirely below the waterline the same fluctuation of water height in the compartment accompanies the ship's movement in a seaway as in the above case of a damaged waterline compartment except that, due to the compression and expansion of the air bubble above the water, the amount of water movement is less; but the principle is the same.

With the lost buoyancy conception in mind, let us consider initial stability characteristics of a damaged ship.

(*a*) *Change in draft.*

The buoyancy of the flooded volume which has been lost to the ship must be exactly compensated by buoyancy of the layer of the hull which is immersed due to the increase of draft; that is,

$$\Delta D(A-a)=a(D-X) \tag{16}$$

or

$$\Delta D=\frac{a(D-X)}{A-a} \tag{17}$$

Where ΔD = increase in mean draft.
a = area of water plane in bilged compartment.
D = original draft.
X = distance from keel to bottom of bilged compartment.
A = area of original intact water plane of ship.

(*b*) *Change in initial stability.*

Since the compartment is, under the lost buoyancy conception, considered as part of the sea, the flooding does not add any weight to the ship. The weight of the ship remains unchanged but the buoyancy of the flooded compartment which is lost is compensated by the added buoyancy due to increased mean draft. It also follows that flooding under this conception has no effect on the center of gravity of the ship, that is, the center of gravity remains fixed. Hence, any change in stability, i.e., in the value of GM, must be due to a shift in the position of M.

The shift in the metacenter may be considered to consist of two factors. First, the metacenter is determined with reference to the center of buoyancy, which must move due to the fact that the buoyancy lost is below the original waterline and the compensating buoyancy is added above the original waterline. Second, the distance $\overline{BM}$ will also be changed because its value depends upon the moment of inertia of the waterline, a change of which results when the damaged compartment is considered as having been lost to the ship.

Therefore,

$$\Delta M=\Delta B+\Delta\overline{BM} \tag{18}$$

Where ΔM = movement of metacenter.
ΔB = movement of center of buoyancy.
$\Delta\overline{BM}$ = change in value of metacentric radius.

The change in the position of the center of buoyancy multiplied by the volume of the ship must equal the distance between the center of volume of the lost buoyancy and center of volume of the added buoyant layer multiplied by the lost buoyancy (equation of moments), that is,

$$\Delta B\cdot V=v_1\frac{(D+\Delta D-X)}{2}, \text{ or} \tag{19}$$

$$\Delta B=\frac{v_1}{2V}(D+\Delta D-X) \tag{20}$$

Where V = displacement volume of ship.
v_1 = volume of bilged compartment up to old draft (see equation (17)).
D = original draft of ship.
X = height of bottom of compartment above keel.

Also, it can be proven that

$$\Delta\overline{BM}=-\frac{i}{V}-\frac{d^2Aa}{V(A-a)} \tag{21}$$

Where $\Delta\overline{BM}$ = change in value of metacentric radius.
V = displacement volume of ship.
i = moment of inertia of water plane in bilged compartment about its neutral axis.
d = horizontal transverse distance from C.G. of bilged compartment to center line of ship.
A = area of original intact water plane of ship.
a = area of water plane in bilged compartment.

Substituting the values of ΔB from equation (20) and $\Delta\overline{BM}$ from equation (21) in equation (18), we have

$$\Delta M=\frac{v_1}{2V}(D+\Delta D-X)-\frac{i}{V}-\frac{d^2(Aa)}{V(A-a)} \tag{22}$$

$$\therefore\quad G_3M_3=GM+\frac{v_1}{2V}(D+\Delta D-X)-\frac{i}{V}-\frac{d^2(Aa)}{V(A-a)}\cdot \tag{23}$$

The above mathematical summary may be stated as follows: When a compartment is partially filled and in open communication with the sea, the change in metacentric height is composed of three factors. The first may be considered to represent the change due to the increased draft caused by loss of buoyancy equivalent to the weight of the flooding water and causes an increase in stability. The second factor may be considered to represent the free surface effect of flooding water and causes a loss in stability. The third factor may be considered to represent the change in initial stability due to the fact that the amount of flooding water fluctuates as the ship works in a seaway; this factor also causes a loss in stability. **Hence, free communication between the sea and a partially flooded compartment always results in less stability than if communication did not exist.**

(*c*) *List effect.*

The list produced by this type of flooding may be determined, as in other cases, by an equation of moments. The exact application is involved but for small angles (angles up to about 10°) the equation may be assumed to be of the same form as formula (3). This assumption, in addition to the approximations accepted in *Art. 3-25(c)*, is dependent upon the approximation that the secant of the angle equals unity. Thus

$$\tan\theta = \frac{w_1 \times d}{W \times \overline{G_3M_3}} \qquad (24)$$

Where θ = angle of list.

w_1 = buoyancy of flooded compartment up to a waterline parallel to the original waterline before flooding but at a height equal to the new mean draft.

d = horizontal transverse distance from C.G. of flooded compartment to center line of ship.

G_3M_3 = new value of GM (from formula (23).

It should be noted that, as in the case in *Art. 3-26*, the angle of list is increased by the reduction in the value of GM. In the present instance this reduction is due not only to the free surface effect represented by the term i/V but also to the variable amount of water flooding as represented by the term $\frac{d^2(Aa)}{V(A-a)}$.

(*c*) *Change of trim.*

Here again we may, for moderate cases, assume the proportionate loss of longitudinal stability to be negligible. Change in trim is sensibly that determined by the formulas given in *Art. 3-25.*

3-27. Effect of flooding on range of stability.

Discussion has so far dealt with initial stability, that is, with the effect of the three types of flooding on the metacentric height. This is, however, not the complete story. Flooding also affects the range of stability. This effect is a complex combination of primary and secondary effects, a mathematical discussion of which will not be attempted. It may be stated that for exact results the only method of determining this effect is to make a complete stability calculation for each case of flooding. Qualitatively, however, the previous discussion together with that in *Art. 3-14* should make the following observation apparent:

(a) The increase in initial stability in the case of complete flooding tends to increase the range of stability. In both types of partial flooding the change in initial stability will be additive or subtractive depending on the relative values of the positive and negative terms of the equation. If an increase in initial stability results, this factor in itself tends to increase the range of stability. If a decrease in initial stability results, a corresponding decrease in range of stability will follow.

(b) All three types of flooding decrease the freeboard by an amount equal to the increase in draft, and this decrease in freeboard always results in decreased range of stability. In the case of complete flooding this loss may reduce the range to a dangerous value even with the increased initial stability. With either type of partial flooding, where the change of stability is never more than a moderate increase and is frequently a decrease, the loss of freeboard under the modified initial stability condition is usually serious and frequently disastrous.

(c) The list which results in all three types of flooding, except where the flooded compartment is symmetrical with respect to the fore-and-aft center line, further adversely affects the range of stability on the low side of the vessel.

(d) Longitudinal stability is usually so great that in any type of flooding the loss of stability is of secondary importance.

3-28. Effect of rapid flooding.

Rapid flooding can occur only when the flooded compartment is in free communication with the sea. The study of statical considerations involved is, therefore, similar to that indicated in *Art. 3-26*. When an explosion of a mine, bomb or torpedo occurs in intimate contact with the ship's side, the shell plating is destroyed over a large area, as much as several hundred square feet. The sea water rushes into the adjacent compartments and the effect on the stability of the ship is not unlike that of a large weight being dropped on the deck edge or into the hold off center. The initial list or heel of the ship cannot be determined from equality of static moments; dynamic effects must be taken into consideration. In other words, the dynamical stability of the ship is the governing factor in determining the initial angle of heel. To show what this may amount to, let us consider Fig. 27. Curve A is the curve of statical stability of the ship of Plates I and II for 1,120 tons displacement; it is similar to curve 5 of Fig. 14, except that the ordinates are righting moments instead of righting arms and the value of the transverse metacentric height is taken as 1.90 ft. instead of 2.64 ft. Curve B is a similar curve for the ship with two wing oil tanks on one side flooded and in free communication with the sea, which has reduced the metacentric height to 1.5 ft. Curve C is the heeling moment curve of the flooded compartments, a cosine curve. It will be noted that curve B intersects curve C at an inclination of 10° 20′. In other words, if the flooding is slow, the ship will slowly rotate until a list of 10° 20′ is reached, when equilibrium is again established. But if the flooding is very rapid, the initial inclination will be much greater. In such a case, we must consider an equality of energies and not an equality of statical moments. The work done by the water in the tanks at ae is represented by the area OTae, while that required to incline the ship to this angle is represented by the area Oae. The excess energy possessed by the admitted water will, therefore, cause the ship to heel to 20° 40′, at which angle the area abc is equal to the area OTa. In other words, when the damage is done, the ship will immediately take a heel of 20°

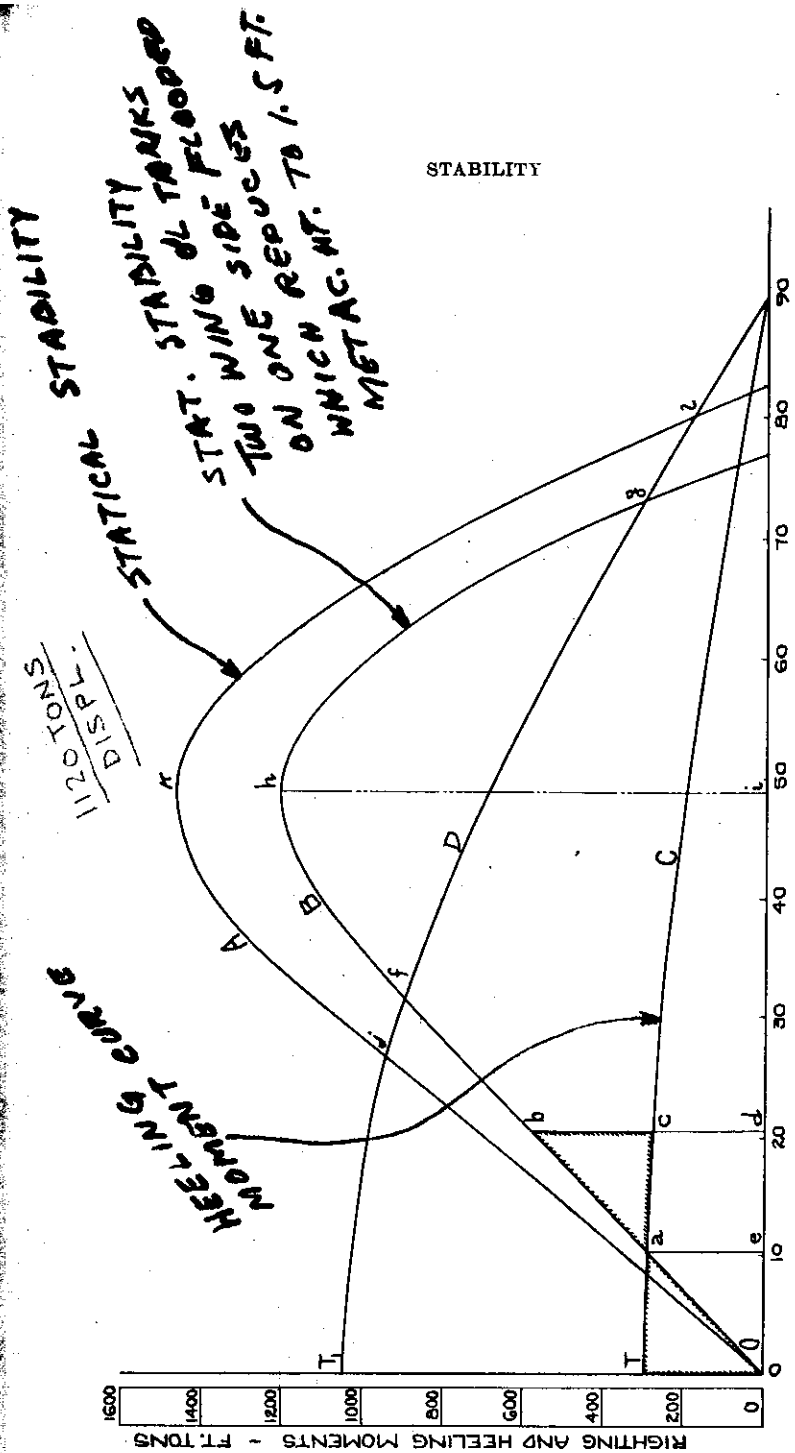

Fig. 27—Dynamic Effects of Rapid Flooding

40′, then roll back towards the erect, and finally take a steady list of 10° 20′. Now if sufficient damage were done to produce the rapid flooding represented by curve D, such that area OT_1f is greater than area fhg, the ship will capsize, although the maximum upsetting moment OT_1 is less than the ship's maximum righting moment hi. If the initial metacentric height of the ship had been such that curve A were the curve of statical stability in the damaged condition, damage represented by curve D would not have been sufficient to capsize the ship, because area jKl is greater than area OT_1j.

Section F—Rolling, Pitching and Damping Apparatus

3-29. Oscillations of a ship in a seaway.

A ship under way among waves is subject to four different kinds of oscillations, vertical oscillations about its normal plane of flotation and rotary oscillations about the three principal axes. Vertical displacement of the ship is known as **heaving.** Rotary oscillation about the vertical axis is called **yawing,** and its principal effect is to make steering a steady course more difficult. Rotary oscillation about the longitudinal axis is called **rolling.** This is the most important of all the four kinds of oscillations and has the greatest amplitude. Rotary oscillation about the transverse axis is called **pitching.** While the angular amplitude of pitching is much smaller than rolling, the linear motion at the ends of long ships may be very great, sufficient to produce heavy pounding forward and to cause partial emergence of the propellers aft. Rolling is intimately related with transverse stability, pitching with longitudinal stability. Since the transverse stability of a ship is much less than its longitudinal stability and the amplitude of rolling is much greater than that of pitching, the emphasis in the discussion of oscillations of ships is laid upon rolling. Pitching is referred to as necessary for an understanding of the special considerations which apply to it. Yawing and heaving have little effect on stability and therefore little further reference is made to these in the ensuing discussion.

The axes about which rotary oscillations occur are not clearly defined. In general, these axes are not far from the center of gravity

of the ship and this point is therefore usually considered the center of oscillation.

3-30. Manner in which sea waves set up rotary oscillations.

Suppose a ship is floating at rest in still water. A wave system approaches from the left. As the wave disturbance moves by the ship, the surface of the water changes from the horizontal. Take the case when the ship is at the mid-height of the wave, Fig. 28A. Figure 28B is an enlarged view of Fig. 28A and shows more clearly what has happened. The volume of displacement has changed shape from WOLKW to W′OL′KW′, consequently the center of buoyancy has moved from B to B′. We have then a couple tending to incline the ship from the vertical in such a manner as to make her waterline parallel to the wave surface. This tendency is present whenever the surface of the water is not perpendicular to the plane of symmetry of the ship.

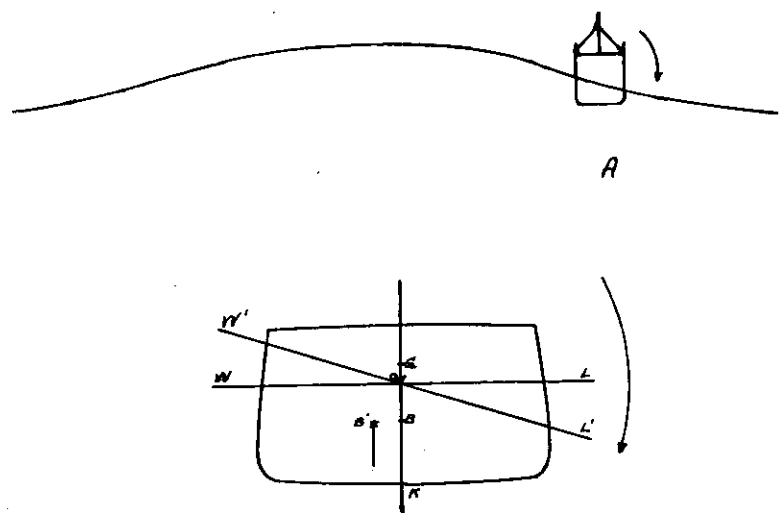

Fig. 28 B

Similarly a wave system striking the ship end-on, will cause a longitudinal displacement of the center of buoyancy and thereby set up pitching. If the ship is long enough to bridge one or more waves from crest to crest, heaving will also be set up. Waves striking