Some Mechanical Features in Anti-Submarine Weapons

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The paper describes—by reference to anti-submarine weapons used in the 1939–45 war—some of the features in the design of underwater armaments that are peculiar to this class of mechanical engineering. A brief description is given of how an attack on a submarine by a ship is carried out either with depth charges dropped from the stern or with projectiles discharged ahead ("Hedgehog"). Features of the weapons of mechanical interest are described under the headings of weapon discharge gear, effect of explosions, safety requirements, and aircraft depth charges. Rails and throwers, including the method of their remote control, for the discharge of depth charges, and the mounting for the Hedgehog, are described. The importance of preventing the explosion of one charge in a pattern having an adverse effect on the remaining charges is discussed. Safety requirements which must be taken to prevent weapons exploding prematurely are described and illustrated. Finally, the method of investigating the behaviour of the form of depth charge dropped from aircraft is described, illustrating an aspect of hydro-ballistics.

DESCRIPTION OF WEAPONS AND THEIR APPLICATION

The Depth Charge. The development of explosive charges fired underwater for destroying submarines came to the fore immediately after the outbreak of the 1914–18 war. In October 1914, Admiral Jellicoe requested the immediate development of a "mine" to be fired by hydrostatic pressure for this purpose, the mine to be triced up astern and let go when over the estimated position of the submarine.

Meanwhile, a civilian—Mr. H. J. Taylor—had on his own account designed a hydrostatically operated pistol for such a purpose. He had a sample of his pistol made, and arranged for it to be tested at the Battersea Polytechnic where he was then an instructor. Mr. Taylor proved as resourceful in finding a means of testing his pistol as in designing it, for when it was discovered that a pressure head of 80 feet required for operating it was not immediately available, he took over some pipes intended for building operations that were lying around; by erecting them vertically end to end he provided himself with a test tank of the necessary depth in which the pistol could be made to operate by lowering it from the top. Trials on the pistol having proved successful, details of it were forwarded by Mr. Taylor to the Admiralty.

The net result was that in June 1915 Mr. Taylor was invited to join H.M.S. *Vernon* to work on this project; he thus became the first civilian member of what is now known as the Admiralty Mining Establishment, from which he retired only as recently as December 1945.

It is of interest to note that it was in Mr. Taylor's invention that the ball lock mechanism was first introduced; this device for securing and releasing a striker is simple and reliable (Fig. 57) and it has subsequently become a standard feature in armament design, not only in this country, but also with most foreign powers.

The depth charge (Fig. 37, Plate 5) has remained substantially unaltered in form since its inception. It is essentially a cylinder of $\frac{1}{8}$-inch steel plate, 18 inches in diameter and 26 inches long, containing some 300 lb. of explosive; a central tube is fitted to hold the firing mechanism which consists of pistol and primer. The pistol operates when a head of 50 feet has been built up in the primer tube; the rate of water entry can be controlled by bringing into action (by rotating an external handle) one of a series of orifices, the effect of which is to delay the building up of pressure in the tube, and so to increase the time—and therefore, in normal circumstances, the depth—at which the 50 feet head is reached. The primer is coupled to a device termed the primer placer, which permits a 3-inch axial movement of the primer while retaining complete watertightness of the tube.

The damage produced underwater by an explosive charge can be regarded as proportional to the square root of the charge weight W, and inversely proportional to the target-charge distance; lethal damage to a submarine (i.e. rupture of a $\frac{7}{8}$-inch thick pressure hull) will be caused by the explosion of 300 lb. T.N.T. at a distance of 21 feet. The distance at which lethal damage will be produced is therefore proportional to $W^{\frac{1}{2}}$, but as this distance extends in all directions round the charge, the lethal volume is proportional to $W^{\frac{3}{2}}$. To render a given volume of sea lethal to a submarine, it is clearly advantageous to employ charges of the largest practicable size. This argument, however, neglects the finite size of the submarine, since it is only necessary for any one portion of the submarine to be within the lethal volume; it is therefore preferable to distribute the charges in plan and elevation. The actual distribution used in service, termed a "pattern", is a compromise governed partly by theoretical "probability" calculations and partly by practical considerations of the safety of the laying ship, available charges, handling facilities, etc. A pattern consists of two layers each of five charges, the distribution in plan being obtained by rolling three charges from the stern at intervals as the ship proceeds, and discharging one to each side from mortars (termed "throwers"); the distribution in depth is obtained by discharging slightly earlier in time a similar pattern, the charges of which are ballasted to give them a higher sinking speed (see Fig. 38). These ballasted charges are set to fire 100–150 feet deeper than the normal charges. For simplicity of drill, the pattern is time-spaced, so that the actual spacing depends on the ship's speed (usually about 15 knots). A view of the quarter-deck of an escort vessel fitted for handling depth charges is given in Fig. 39, Plate 5.

The normal charge sinks with its axis horizontal, the terminal velocity being 10 ft. per sec. The ballast weight for the faster sinking charge is secured to one end, and by giving the charge an axis-vertical attitude, as well as by increasing the weight, the sinking speed is increased to 17 ft. per sec. The shape of the ballast weight was determined by the consideration that its presence must not interfere with the handling of the depth charge in existing equipment, so that the speed of 17 ft. per sec. represents what could be achieved in practice rather than any theoretically desirable speed.

It is interesting to note, in parenthesis, that the sinking of the standard depth charge provides an example of the "Magnus" effect. In rolling off the rails the charge acquires an angular velocity, and the effect of this superimposed on its vertical velocity is to give it a "lift" in the direction of the ship's motion. The result is to cause the charge to pursue a slanting path which reduces its apparent vertical velocity until the rotation has died down; this takes some little time as the only force tending to

The MS. of this paper was originally received at the Institution on 30th November 1946, and in its final form, as accepted by the Council for publication, on 26th April 1947. *For the Minutes of Proceedings* of the meeting in London on 6th February 1948, at which this paper was presented, see Proc. I.Mech.E., 1948, vol. 158, p. 120.

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reduce the rotation is the surface friction which is of comparatively small magnitude. Experiments have shown that the initial rate of sinking is approx. 6 ft. per sec., and that the

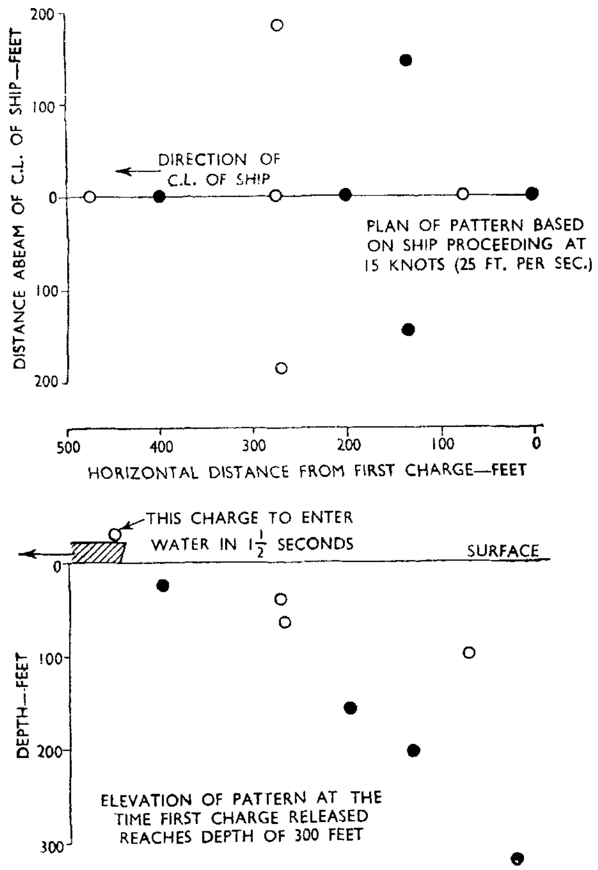


Fig. 38. Plan and Elevation of Depth Charge Pattern

○ Normal charges.
● Ballasted charges.

terminal velocity of 10 ft. per sec. is only reached at a depth of about 200 feet.

A diagram giving a simplified explanation of the Magnus effect is given in Fig. 40; it may be remembered that it was

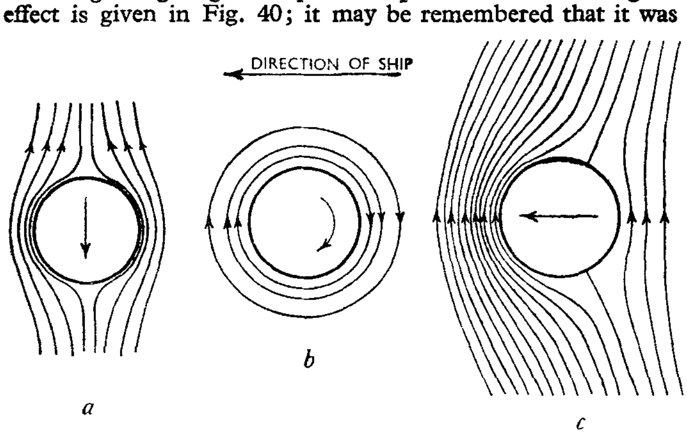


Fig. 40. Diagrammatic Explanation of "Magnus" Effect showing how Rotation of a Body in a Moving Stream can produce a Force on the Body transverse to the Stream

(*a*) Streamlines due to translatory motion alone.
(*b*) Streamlines due to rotation caused by surface friction.
(*c*) Combined effect of both sets of streamlines, producing resultant pressure in direction shown.

employed for the propulsion of the Flettner rotor ship. Another place where the Magnus effect is apparent is on a sweep wire towed at an angle to a ship's axis. The lay of the rope causes a rotation of the water round the wire, and the resultant lift is used to counteract the sag in the sweep wire due to gravity.

Method of Making an Attack. To understand what performance is required of a ship-borne anti-submarine weapon, it is necessary to have some slight knowledge of how an attack on a submarine is made. Assuming that a submarine has been located in the asdic beam, the ship's captain endeavours to con the ship so that its stern can be brought over the spot where it is estimated the submarine will be by the time the charges have reached it. The depression of the asdic beam is, however, fixed at a comparatively small angle, so that the submarine passes out of the cognizance of the attacking ship at a range not less than about three times the depth of the submarine (see Fig. 41). Even under favourable conditions some 30 seconds must elapse from the time contact is lost with the submarine until the

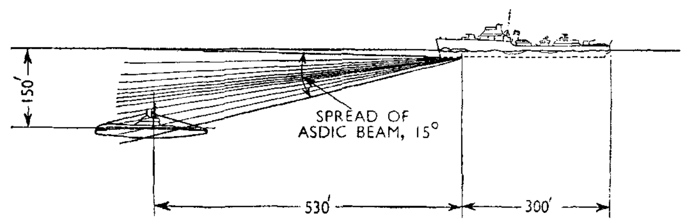


Fig. 41. Diagram showing distance at which Attacking Ship loses Asdic Contact with Submarine

Distances are typical only.

depth charges are discharged; to this must be added the time of sinking of the charges to their exploding depth, which in the case of a submarine at a depth of 200 feet may be another 15 to 20 seconds.

It will be clear that after the elapse of this length of time, there must be considerable uncertainty of the exact position of the submarine in plan due not only to the instrumental and human errors in estimating the course and speed of the submarine from asdic data while the ship was in contact, but also to the evasive action on the part of the submarine commander. It is to allow for this uncertainty that the pattern plan is made as large as possible.

This long "blind time" (i.e. time from loss of asdic contact to explosion of depth charges) was not a very serious defect in the stern-drop method of attack, so long as submarines had comparatively slow underwater speeds (e.g. 6 knots maximum) and were likely to be encountered at depths not exceeding 200 feet; this was roughly the state of affairs in the period between the wars. With the improvement in the ability of submarines to withstand punishment, and with their ability to dive to greater depths, a material decrease in the blind time became a necessity if attacks were to be effective, and an obvious step in this direction was to increase the sinking speed of the weapon. This, however, was not possible with depth charges as will be seen from a consideration of the effects of the explosions on the attacking ship. The first place in a ship to suffer damage from an underwater explosion is the engine-room, where the mountings of heavy pieces of machinery are likely to be broken, although steps have been taken to introduce as far as possible resilient mountings to minimize shock effects. The criterion for the safety of the attacking ship thus becomes the distance of the explosion from the after engine-room-bulkhead, and for charges of 300 lb. of T.N.T. the distance closer than which explosions cannot be permitted to occur is shown diagrammatically in Fig. 42.

The explanation of the rapid reduction in range at depths shallower than 100 feet is that when a charge explodes close to the surface, the path traversed between explosion and ship by the shock wave reflected at the surface is only very slightly longer than the direct path. The reflected wave will therefore arrive while the direct wave is still present, but as the reflected wave has suffered reversal in phase at the surface, it is—in effect —a tension wave; the tension will cancel any compression due to the direct wave, and so will reduce the effect of the latter. The increase in range below 250 feet is due to the fact that the projected area of the ship's bottom normal to the line of propagation of the shock wave is increasing.

On the diagram in Fig. 42 are also plotted depth-time curves for various sinking speeds based on an assumed ship's speed of 15 knots, and it will be seen that if explosions are required at a depth of 50 feet—as they obviously must be for attacking shallow submarines—a sinking speed much in excess of 10 ft. per sec. is not permissible. Since a slow sinking weapon is unavoidable for attacking shallow targets, and a fast sinking weapon desirable for attacking deep targets, the only solution would be to carry both forms—a solution that is unacceptable in view of the complication arising from the necessity for having magazine facilities and discharge gear appropriate to both forms. The possibility of fitting the fast sinking weapon with a drogue,

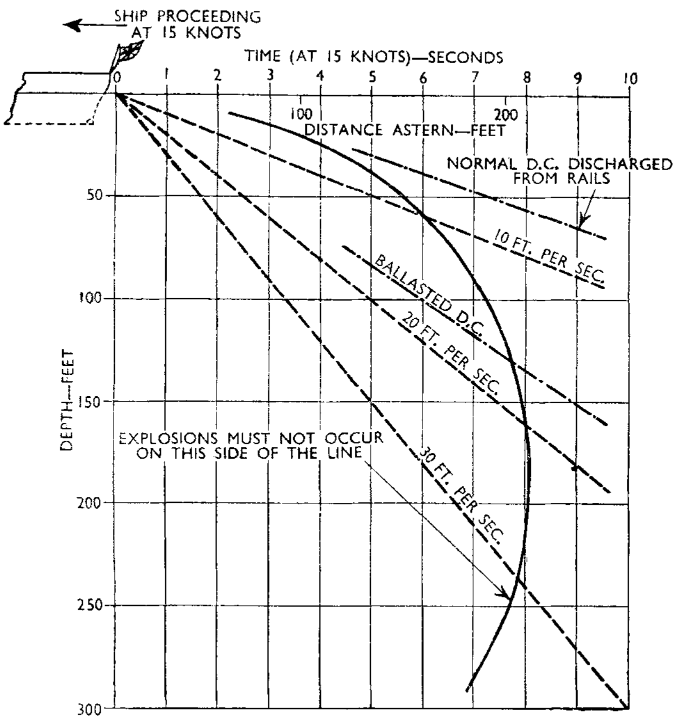


Fig. 42. Diagram showing Minimum Distance Astern and Depth for Explosions not to Damage Attacking Ship

or other means of reducing its speed, when required for a shallow attack, is ruled out by safety considerations, as failure of the speed-reducing device to work might well result in damage to the ship.

Weapon Discharged Ahead. If the weapons could be discharged ahead, not only would the blind time be reduced to the sum of the time of flight in air and time of sinking through the water, but a high sinking speed would also be advantageous, since for the safety of the ship the charges must have exploded before she has approached too near. It would be possible to project depth charges ahead, in which case the range would require to be 350 yards which would call for a thrust of 90 tons. Such a thrust would require a considerable amount of deck stiffening, and this scheme was only adopted in two ships, a photograph of the armament of one of which appears in Fig. 43, Plate 6.

An alternative was to project ahead small charges to explode only on contact with the submarine, and to compensate for the small likelihood of a direct hit by any one charge by employing a large salvo. Trials showed that the weight of explosive to rupture the pressure hull of a submarine when the charge is exploded in contact with the casing 4 feet above it is 30 lb. if the most efficient explosive available is used.

The use of contact fired charges has the following further advantages:—

(*a*) Their operation is independent of the depth of the submarine.

(*b*) The explosion of one or more charges should (at least in theory) indicate a "kill".

(*c*) The water is not disturbed by large explosions which —until the disturbance is dissipated—tend to prevent effective use of the asdic.

The chief defect in a contact fired charge is that in the absence of a target it is not possible to produce an explosion. There are occasions when an explosion, even if not immediately endangering a submarine, may deflect its commander from any course of action he is pursuing at that moment, such as preparing to fire torpedoes at a convoy. Another objection—it cannot be called a defect—is that a submarine destroyed by this type of charge often leaves no evidence of its destruction behind it; this rendered the weapon that was developed on the foregoing lines a little unpopular with the commanders of some escort vessels, since to establish a kill the Admiralty were insistent on visible evidence in the form of recovered clothing, lockers, and other debris that floated to the surface after the destruction of a submarine.

The "Hedgehog". A weapon on the above lines was developed during the war and brought into service at the end of 1941. The projectiles were fired from spigots, and the appearance of the spigot mounting gave the weapon the name "Hedgehog"—very appropriately as can be seen from the view given in Fig. 44, Plate 6. The projectile weighed 62 lb. and contained 34 lb. of the explosive known as "Torpex"; the rate of sinking was 24 ft. per sec. A salvo consisted of twenty-four projectiles fired to produce a pattern in the form of a circle 130 feet in diameter, the mean range of projection being 200 yards. Fig. 45, Plate 6, is a view of the pattern of the splashes made by the projectiles striking the water as seen from the ship.

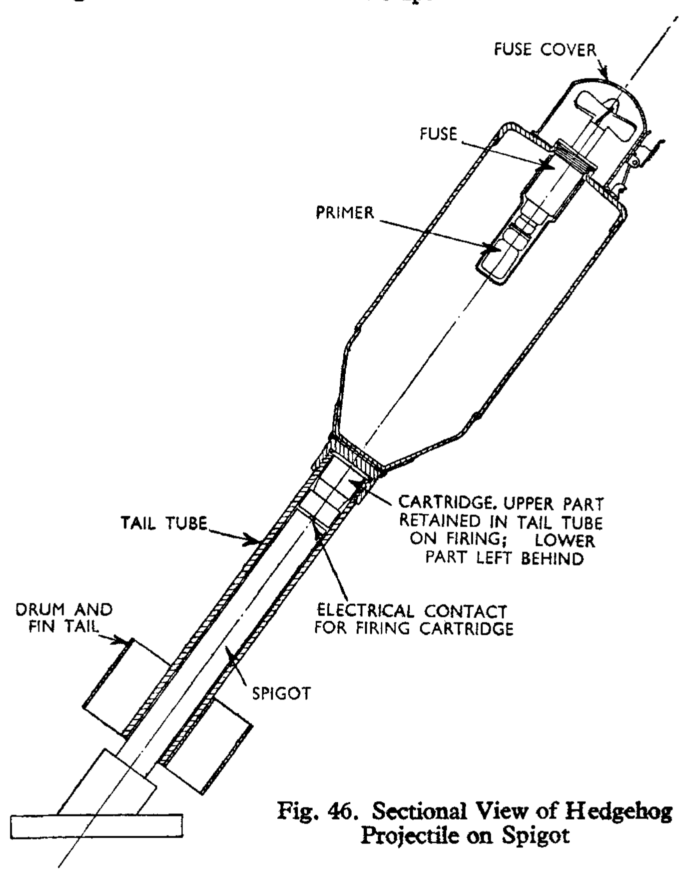


Fig. 46. Sectional View of Hedgehog Projectile on Spigot

The variations in range and angle to produce the pattern are obtained by suitably aligning the spigots in elevation and bearing, the same weight of propellant charge being used for all projectiles.

A sectional view of the projectile on its spigot is given in Fig. 46. One feature of interest is that the tail vanes are set in a helix of approximately 19 feet pitch, so as to impart a spin to the projectile when in the water. The object of this is to reduce dispersion due to any slight asymmetry in the manufacture of the tail. Without spin, such asymmetry can lead to the projectile wandering farther and farther from its true path as it descends; with spin, the asymmetry will cause the projectile to pursue a spiral path in which the departure from the true path is constant for all depths.

It can be shown by calculation that, for attacks on a submarine at depths from 0 to 300 feet, the probability of inflicting lethal damage to a submarine with Hedgehog is about three times that with depth charges. In practice, the ratio of probabilities is rather better than this, in favour of the Hedgehog; the reason for this lies chiefly in the difficulty of conning a ship so as to place its stern at the desired spot—a practical point which has to be neglected in computing probabilities. Not only is this difficulty avoided in using the Hedgehog, but as the mounting of the latter has to be stabilized to neutralize the effects of roll, it is possible, by deliberately inclining the spigots, to fire over an arc extending to some ± 30 deg. from the centre line of the ship; it is consequently only necessary to keep the spigots directed at the target and not the centre line of the ship.

Nevertheless, the depth charge played an important part as an anti-submarine weapon, for out of the total number of German U-boats known to have been sunk by British surface forces some 75 per cent were destroyed by depth charges. It should be remembered, however, that for the first two years of the war there was no other ship-borne weapon available*.

WEAPON DISCHARGE GEAR

Mechanical features of general interest are rather lacking in the weapons themselves; the discharge arrangements for the weapons, however, provide several features of interest in mechanical design and these are described in some detail.

Depth Charge Traps. As already stated, depth charges are placed by being either rolled over the stern or projected on the beam. For stern release, charges are rolled down an angle-iron structure having a 10 deg. slope, a guard rail being fitted at the top to prevent the charges jumping the release levers or being lifted by the action of heavy seas. To release a charge, and bring the next charge to the ready position, a device termed a "trap" is employed; this is illustrated in Fig. 47, and one essential feature of the arrangement is to ensure that only one charge can be released at a time. To operate the trap, the shaft carrying the actuating lever is rotated clockwise (as drawn); the weight of the ready charge then depresses the rocking lever and the charge rolls out. The same action has resulted in lifting the toe of the resetting lever, thus restraining the next charge from moving. On releasing the shaft, the weight of the standby charge forces down the resetting lever, which action restores the rocking lever to its safe position; the standby charge is thereby free to roll into the ready position. To ensure that the charges do not jam between the toes of the levers and the top rail, the gauge between top and bottom rail is toleranced to $+\frac{1}{8}$ $-\frac{1}{16}$; this is fairly close for a fabricated structure, and calls for accurate manufacture. The "working" of a ship can alter the dimensions, so that a periodical check must be made while the ship is at sea. Freedom of movement of the working parts is of vital importance, and the design requires careful consideration when the gear is exposed to the corrosive action of sea-air and sea-water such as can occur in the stern of a small ship. The levers are made of steel plate, and bushed with gunmetal, the journals being naval brass, and this combination coupled with lubrication by grease-gun using anti-freezing grease has been found satisfactory.

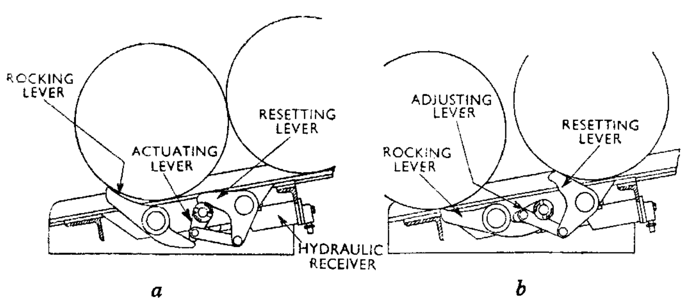


Fig. 47. Diagram of Operation of Depth Charge Trap

(*a*) Ready charge held.
(*b*) Charge released; next charge restrained.

Depth Charge Throwers. Unlike most other cylindrical shaped weapons, the depth charge is projected with its axis transverse to the barrel of the mortar. The depth charge is therefore carried on a semi-circular tray secured to a piston, as shown in Fig. 48. To prevent loss of piston and tray, arrangements are made to arrest the motion of these towards the end of the stroke by means of the arrestor cylinders mounted on each side of the barrel (see Fig. 49); the ports in the arrestor are arranged to give as nearly as possible a uniform deceleration. Just before the arrestor piston enters its cylinder, the end of the piston reaches the exhaust ports in the barrel. The depth charge is projected 67 yards, the axial reaction being approximately 25 tons. The fluid employed is a mixture of glycerine and lime water in equal proportions by volume, the lime being added to neutralize any acid in the glycerine.

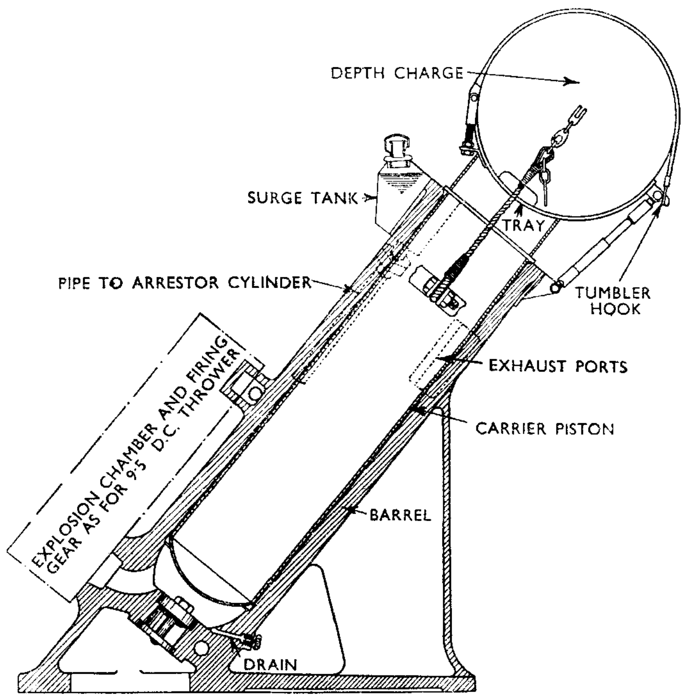


Fig. 48. Sectional View of Depth Charge Thrower

The charge is secured to the tray by means of the strop and tumbler hook as shown in Fig. 48. The initial motion of the piston results in the spigot of the tumbler hook being withdrawn from the sleeve attached to the barrel, thus freeing the charge.

The cartridge is fitted in an explosive chamber attached to the barrel and is fired by means of a spring-loaded striker. The striker is lifted against the pressure of the spring by a wedge until—when the wedge is completely withdrawn—the striker is released.

Experience in the 1939–45 war showed the necessity for guarding against the non-operation of traps and throwers due to accumulations of ice and snow. It was found necessary to enclose rails and throwers as far as possible with steel and canvas covers to prevent large accumulations, and to run steam-heating coils in suitable locations to keep the working parts free.

* In the above account, for security reasons a great deal has of necessity been left unsaid. Some obvious improvements or alternatives will suggest themselves, and it can be admitted that by the end of the war better equipment, better weapons, and a better technique were in service use; at the same time, the position described represents very fairly the conditions under which anti-submarine warfare was waged for the first half of the war—a period which covers the major portion of the Battle of the Atlantic.

The elevation of the tray of the thrower from the deck makes loading an awkward operation, and for this purpose the loading racks—prominent in Fig. 39, Plate 5—were introduced. The ready charge is carried on the top tier, whence it can be pushed on to rollers in line with the tray and so slid into position; the remaining tiers are used for stowage. The charges are raised by the use of a davit or parbuckle.

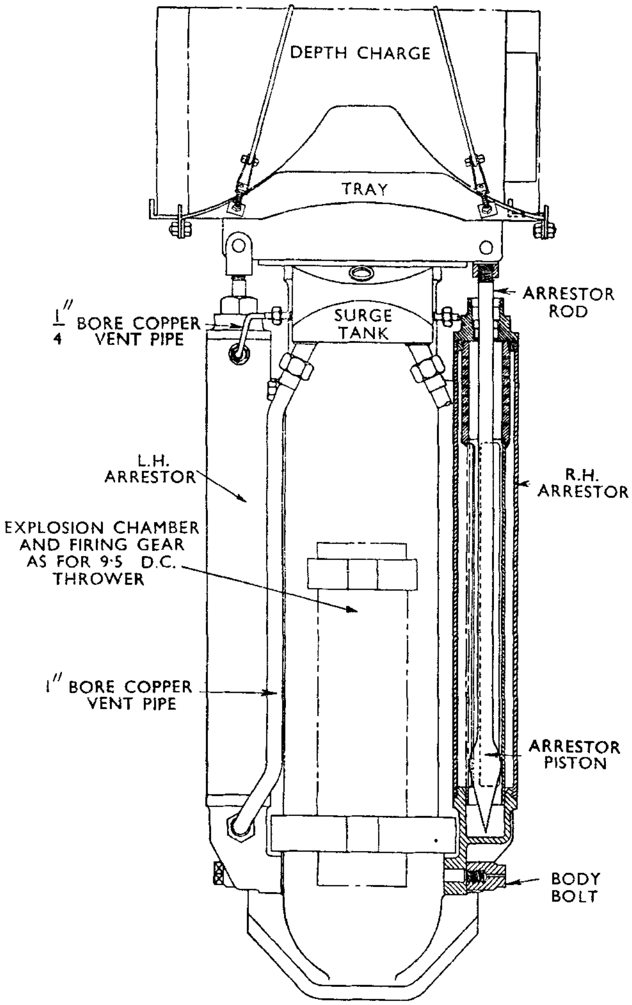


Fig. 49. Section through Arrestor Cylinder

Remote Control of Discharge Gear. The presence of a depth charge crew is always necessary during anti-submarine attacks to carry out reloading, and this crew is therefore available to operate the traps and throwers manually. It is very desirable, however, that the officer of the watch should be able to release a pattern of depth charges in an emergency from the bridge before the depth charge crew could be summoned, and this requirement called for some method of remote control. This was originally achieved by hydraulic methods; a hydraulic jack (or receiver) was fitted to each trap and thrower, and was connected to a hand pump on the bridge. One stroke on the hand pump was sufficient to operate its corresponding jack, the piston of the receiver being subsequently restored to its normal position by means of a spring.

A subsequent requirement was to incorporate with remote control automatic timing of the discharges so that a pattern of the correct shape (see Fig. 6), was always delivered. To avoid the long runs of hydraulic piping and also to reduce the space occupied on the bridge, an electro-hydraulic system was evolved which is illustrated diagrammatically in Fig. 50. A local hydraulic system consisting of hand pump and accumulator is installed at the stern of the ship, the operation of the receivers being controlled by electrically operated valves. The valve solenoids are each energized at the appropriate moment by means of electrical contacts made by cams driven by a spring-driven governor-controlled motor. This motor is released by electrical control from the bridge, and, once released, runs until the cams have completed one revolution (giving the sequence for one pattern) when it stops automatically and is then ready for the next operation.

A sectioned view of the solenoid-operated valves is given in Fig. 51, and it will be seen that a combination of poppet and piston valves is employed. This arrangement was dictated by two requirements—the necessity for keeping loads and friction to a minimum due to limitations in the electrical supply, and the necessity for ensuring no leakage from inlet to delivery when the valve was closed. The maximum working pressure of the hydraulic system is 825 lb. per sq. in., and the load to crack-open the poppet valve at this pressure is 11 lb.; the solenoid is therefore designed to give at least this pull at 16 volts (66 per cent of the nominal voltage), and further to ensure the valve opening there is 0·03 inch lost motion between solenoid armature and valve so that the inertia effect can be utilized. The armature and pole pieces are shaped so that the maximum possible pull is developed at starting consistent with maintaining it as nearly as possible constant through a stroke of 0·3; the shape was determined by trial and error, and the load-stroke curve is shown in Fig. 52.

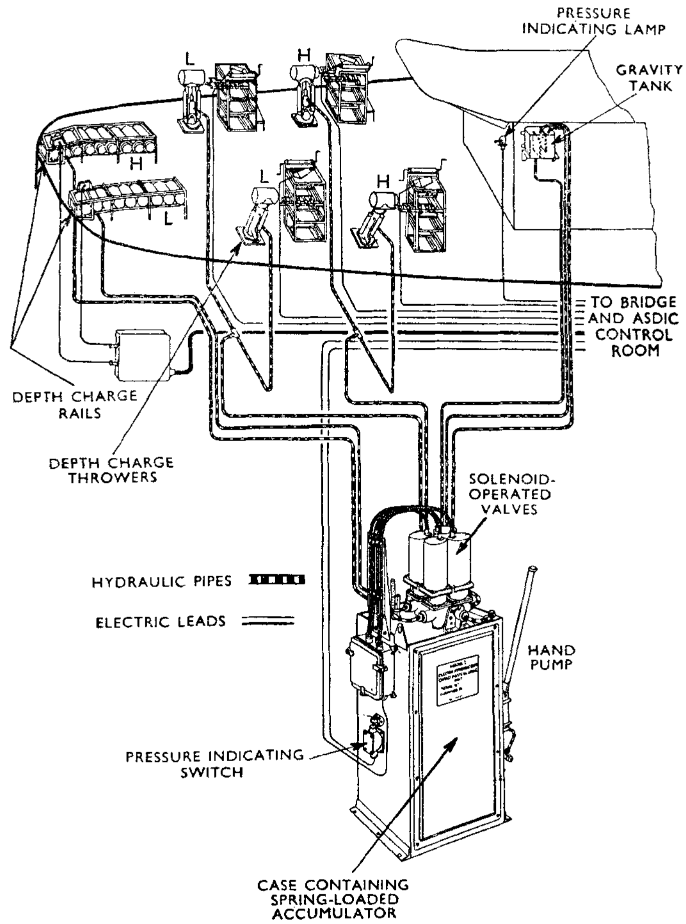


Fig. 50. Diagram of Layout of Electro-hydraulic Release Arrangements for Depth Charges

The central position of the poppet valve necessitated the upper piston working in a sleeve, and in view of the fine clearances this arrangement called for very careful manufacture. The valve body is of bronze, with a "nitralloy" bush in which the valve works. This bush was machined, then—without removing it from the machine—the sleeve was pressed in, and the bore of the combination machined. Without separating the components, the combination was next hardened by nitriding, and then fitted

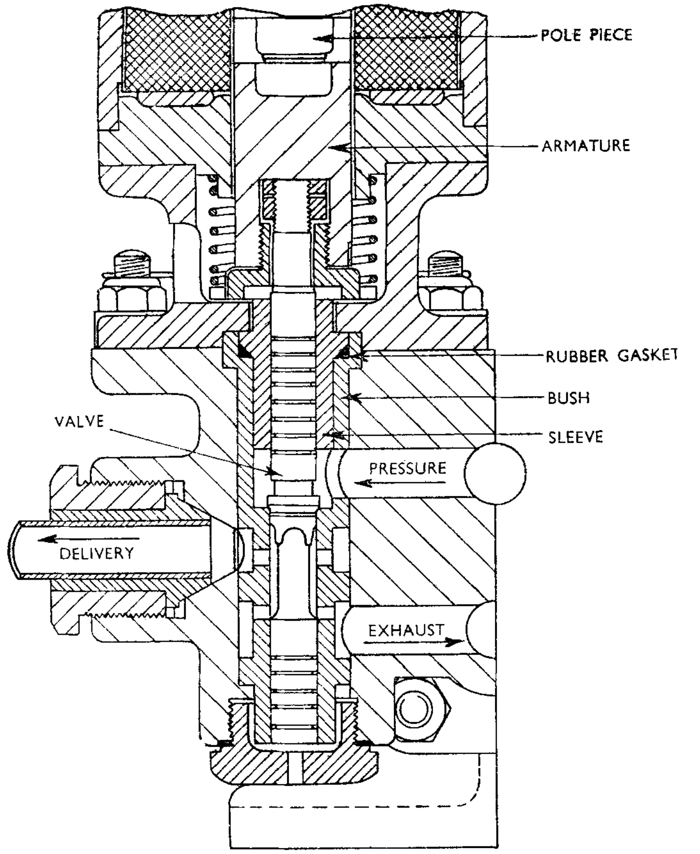


Fig. 51. Sectional View of Solenoid-operated Hydraulic Valve

into the body, being secured by sweating; after that the bore was honed and lapped until the valve (also made of nitralloy and hardened) could be fitted without the specified maximum leakage of 0·1 cu. in. per hour from the high pressure inlet being exceeded. The fitting of the valve is the only occasion on which the sleeve is removed from the bush; a rubber gasket is provided to maintain pressure-tightness of the sleeve seating. Lapping was carried out from the bottom end so that any bell-mouthing occurred at this end, where leakage was comparatively unimportant.

Hedgehog Mounting. This consists of four I-beams mounted parallel to the centre line of the ship, six spigots being carried on each beam. The beams are fitted with end-trunnions so that they can be rocked in a transverse plane to permit of roll correction, the trunnion axes being above the beams to give a compromise between balance of loaded and unloaded mountings (see Fig. 53, Plate 6). The trunnion journals are of cast steel, running in cast

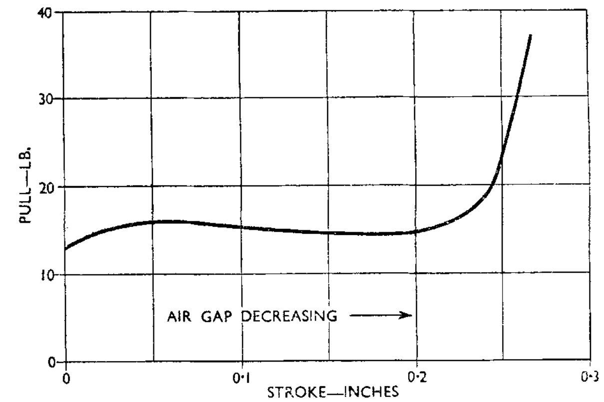


Fig. 52. Load-Stroke Curve for Valve Shown in Fig. 51
Values taken at 16 volts; nominal voltage 24 volts.

steel bearings bushed with phosphor-bronze, lubrication being by grease gun. In rough weather, the grease was washed out of the forward (and most exposed) bearings, so end covers were introduced which served as a palliative. The use of steel, however, meant that more care and maintenance was necessary to ensure freedom from seizure than in the case of the depth charge traps, which could be operated even when upkeep was neglected.

Manual control of rocking is provided by a handle which is connected to one beam through an 80/1 worm gear, the other three beams being operated through a connecting rod. The axial reaction produced on firing is 16 tons, and as the corresponding port and starboard spigots are fired simultaneously, a total reaction of 32 tons has to be sustained. Each pair of spigots is fired in succession, the total time occupied in firing a salvo being two seconds.

The mounting was intended to take the place of a forward gun, but in some ships it was particularly desirable to retain this

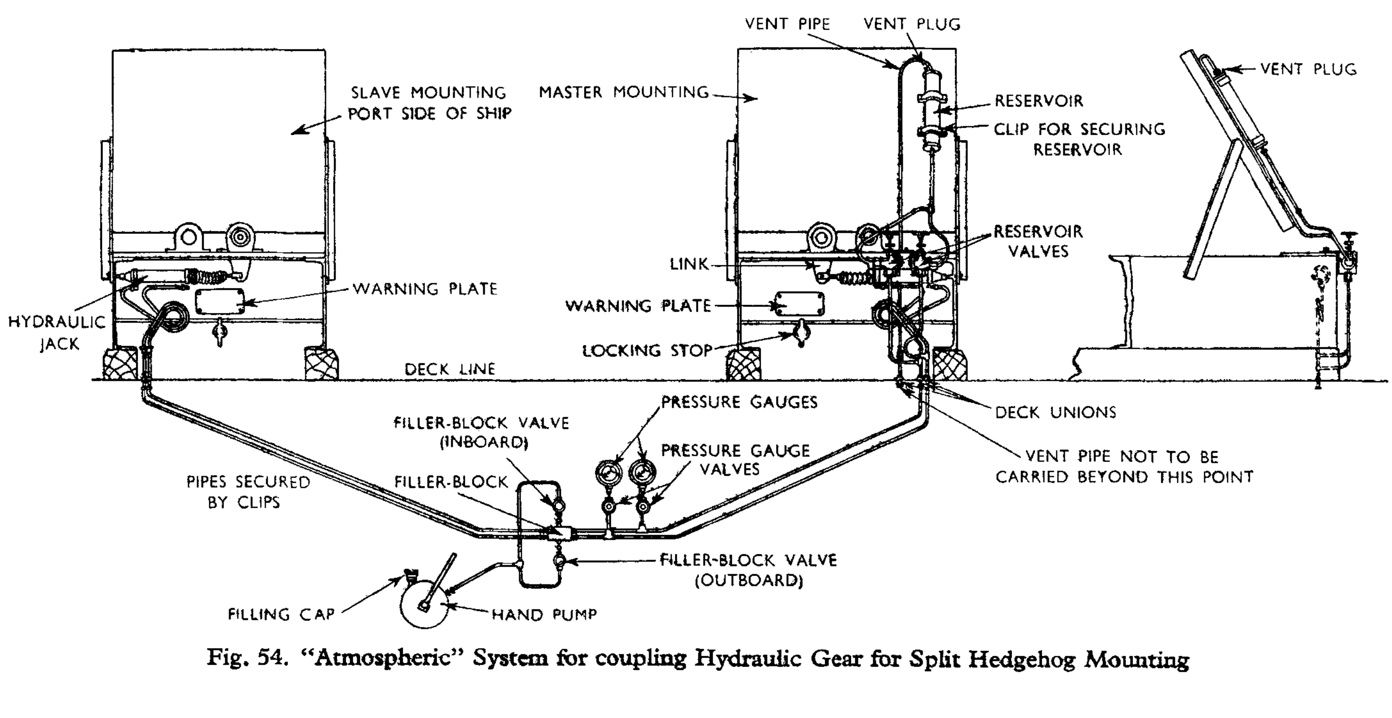


Fig. 54. "Atmospheric" System for coupling Hydraulic Gear for Split Hedgehog Mounting

gun so for these ships the mounting was split into two units of twelve spigots each, one unit being mounted on the port side of the ship and one on the starboard. Since the two units must operate as one, it was necessary to connect them so that when the master unit was operated, the slave unit would follow exactly. The obstruction that would have been caused by a cross-shaft rendered a simple mechanical connexion impracticable, so hydraulic coupling was employed using a closed system operating nominally at about 100 lb. per sq. in.; this pressure was necessary to keep out trapped air which was the chief cause of backlash, i.e. difference in movement of the two units. This arrangement was subject to difficulties due to temperature variations; if the temperature rose much above that at which the system had been filled, the pressure rose considerably, and when it exceeded 500 lb. per sq. in. the mounting became too difficult to train, while if the temperature fell, the pressure might drop below atmospheric pressure and air was drawn in.

A possible remedy was to introduce an accumulator into the system; this was tried but it was found that if the mounting was trained rapidly, there was a tendency for movement of fluid to be divided between the accumulator and the slave jack, resulting in the latter being sluggish in following. The remedy finally adopted is known as the "atmospheric" system and is illustrated diagrammatically in Fig. 54. The normal condition is with both mountings locked in mid-position and the reservoir valves open. When it is desired to train the mounting, the valves are closed before the locks are released; by following this procedure, synchronism between master and slave jacks is maintained within 30 minutes of arc, thus making the performance equal to that of the closed system. It should be added that this accuracy can only be achieved if all trapped air is removed from the system, and the system must be bled after filling until all air is removed. This system had a further advantage over the closed system in that, in the latter, differential leakage past the pistons of the two jacks could lead to a cumulative backlash error; in the atmospheric system the jacks are resynchronized every time the mounting is used.

EFFECT OF EXPLOSIONS

When underwater weapons are discharged in salvos or patterns it is usually necessary to ensure that when one charge in the pattern explodes it does not have any adverse affect on the remainder of the charges. Such adverse affect may take two forms: (*a*) damage may be caused to the other charges so that they are rendered incapable of correct functioning; (*b*) premature operation of the firing mechanism of the other charges may result.

Before discussing these two aspects, it will be desirable to say something about the nature of underwater explosions in their effect on objects at a distance.

Underwater Explosions. The detonation of an explosive charge underwater results in passage through the water of a shock wave which travels (for distances in excess of about 20 times the diameter of the charge, considered as a sphere) at the speed of sound in water—approximately 5,000 ft. per sec. under normal conditions. The pressure in the shock wave rises to its maximum intensity in a few microseconds, and then falls exponentially to about 10 per cent of its maximum value; the subsequent pressure-time history is not fully known and in any case is not of great concern. The maximum pressure falls off inversely as the distance from the explosion.

Some idea of the values involved can be obtained from the following data relating to a 300-lb. charge of T.N.T. At 100 feet from the charge, the maximum pressure is 950 lb. per sq. in. The rate of fall of pressure is such that the pressure has fallen to 40 per cent of its maximum value in one millisecond. The calculated impulse or momentum, i.e. $\int pdt$, over this period will be approximately 0·7 lb.-seconds per sq. in. If this is assumed to act on the circular end of a depth charge, the latter will be given suddenly a velocity of the order of 10 ft. per sec.; the shock sustained can be regarded as equivalent to that resulting from dropping the charge from a height of 18 inches on to an unyielding surface.

Such information, however, is of little use to a designer who requires to know the effect of the shock on component parts of the firing mechanism; in other words, the designer wants the information in terms of acceleration, rather than "impulsive velocity change". To do this is not a straightforward matter, because if the time of application of the impulsive force is small compared with the natural time period of vibration of the item concerned (the usual case), the amplitude of the vibration started will be less than if the acceleration had been longer sustained. Put another way, the value of the acceleration that would produce the same amplitude of vibration, if it were applied in the form of a steady load, as the actual acceleration, depends on the natural time period of the item. For the case cited above, it is estimated that for items having natural time periods of the order of 10 milliseconds the amplitude of vibration produced by the velocity change would be the equivalent of that produced by a steady acceleration of some $200g$.

It is to be noted that when the shock wave reaches the far end of the body (which in the case of the depth charge will be half a millisecond later), the body will be given a blow of nearly equal magnitude in the opposite direction. This double blow must be taken into account in shock calculations, since if it happens to coincide in phase with the existing vibration, the amplitude of the latter may be increased.

Damage to Other Charges in Pattern. The subject of explosive damage to a weapon hardly lends itself to a discussion of principles, as the nature of the damage is so dependent on the particular construction involved. It has been thought preferable therefore to describe one particular example of the effect of the shock wave in producing damage, especially as the example in question provides a good illustration of the double blow just referred to.

In the course of the war, one improvement in explosive technique was the addition of powdered aluminium to certain explosives; a mixture of T.N.T., ammonium nitrate, and powdered aluminium was known as "Minol". The effect of the aluminium is to increase the total reaction time of the explosive without materially affecting the maximum pressure produced; the impulse from Minol will therefore, other conditions being the same, be greater than that from T.N.T. and consequently Minol may be expected to have a greater damaging effect. The introduction of this explosive into depth charges resulted in an increase in their damage radius against submarines of approximately 25 per cent, but it also resulted in an increase in the damage radius among charges in the pattern which it became necessary to investigate.

It so happened that the weakest point in a depth charge was the joint between pistol and charge. Referring to Fig. 55, Plate 6, the pistol is fitted with a washer having three projecting lugs; these lugs engage in bayonet slots in the central tube of the charge. The load required to break the joint by pushing the pistol into the tube (i.e. by shearing the lugs) is about 3 tons with a mild steel washer. The load required in the opposite direction is only about 1 ton, as the first action is to cause the lugs to bend, and these then act as wedges to open the ears of the slot outwards. Any relative acceleration between pistol and charge sufficient to produce this load in this direction will result in breakage of the joint, loss of pistol, and failure of charge.

Since the pistol and charge have different masses and areas exposed to the shock wave, there will be a relative acceleration of one with respect to the other which will be reflected in the deformation of the washer. Examination of the washer after trial will therefore provide some qualitative information on the effects of the shock wave, e.g. one or more lugs sheared indicate inward motion of the pistol (relative to charge); bending of lugs indicates movement according to the direction of bending.

The results of such an examination in a number of trials where the distance, attitude, and orientation of the "target" charge with respect to the exploding charge were varied, are depicted graphically in Fig. 56. At the time these trials were carried out, the primer was not secured by the primer placer (as shown in Fig. 37), but by a comparatively weak joint, the strength of which can be neglected. The pistol-charge joint is therefore the only effective one to be considered, and how the shock wave can cause the observed motions is suggested in the inset to

Fig. 56. The actual values of the forces experienced by the joint will diminish with increasing distance from the explosion, with the result that the inward motion only occurs at ranges up to about 60 feet, whereas the outward motion occurs at greater ranges due to the much lower resistance of the joint in this direction. This accounts for the rather unexpected result that failure takes the form of the pistol being ejected from the charge whether the pistol is pointed towards or away from the explosion.

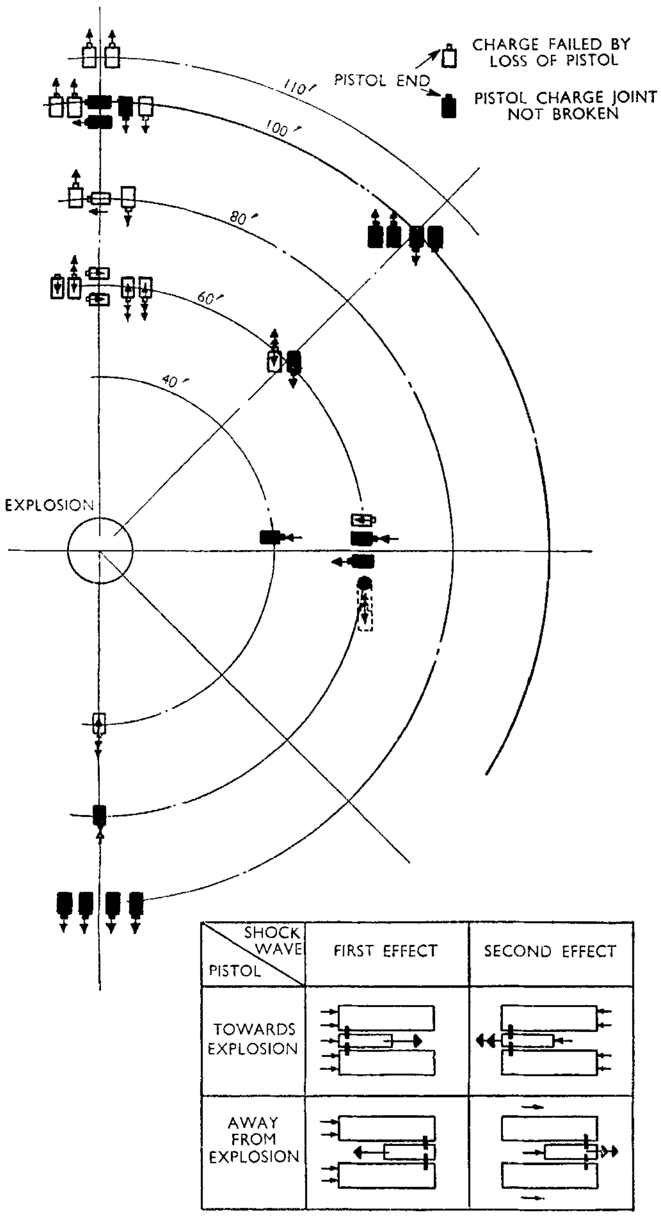


Fig. 56. Diagram showing Damage to Depth Charges in Relation to Explosion

The diagram shows the charges disposed in the vertical plane.

The diagram also exhibits another feature of interest. It will be observed that vertically above the explosion, the joint fails at ranges in excess of 110 feet, whereas in other directions the joint remains effective at a range of 80 feet or a little more. The reason for this is to be sought in the behaviour of the gas bubble produced by the explosion.

At the instant of detonation, the mass of explosive can be regarded as turned into a bubble of gas at extremely high pressure and temperature. As this bubble expands, it imparts kinetic energy to the water surrounding it. When the pressure in the bubble has fallen to the equilibrium value corresponding to the depth, there will still be considerable kinetic energy in the surrounding water so that the bubble will continue to expand until this energy is absorbed. The pressure in the bubble will now be below the equilibrium value, and the whole process is reversed, the equilibrium value being again overshot. Due to energy losses, the bubble does not return to its initial size (that of the solid explosive) but it does contract to a minimum, and then re-expand with explosive violence, producing a second shock wave. This shock wave is probably less severe than the first, but as the bubble will have been ascending during the above process, the second shock will be produced nearer to any target above the charge. Hence *above* the charge, an intensification of damage might be expected as compared with other directions.

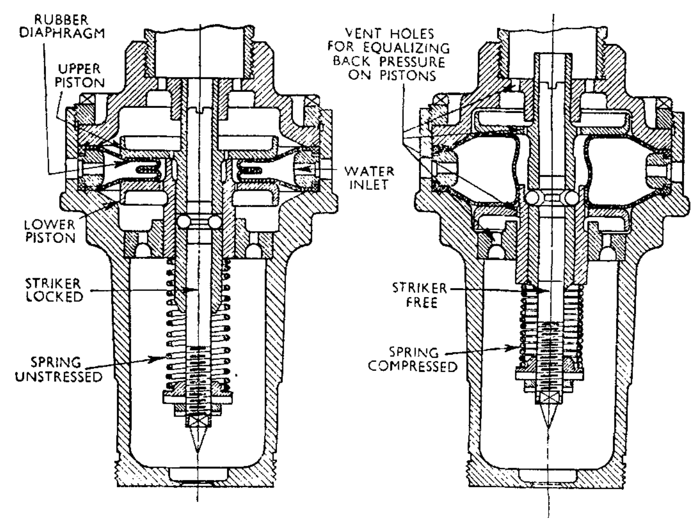
The remedies adopted were to replace the mild steel washer by one of high-tensile steel, and also to alter the pattern so that the upper layer was displaced horizontally with respect to the lower layer (which explodes first) so that the distances between corresponding charges was increased; this modified pattern is the one depicted in Fig. 38.

Countermining. When the firing mechanism of an underwater weapon is actuated by an explosive shock, the weapon is said to be countermined. Countermining of the depth charges in a pattern must be prevented, partly to avoid wasting a charge that might ultimately explode nearer the target, but principally on account of possible danger to the ship laying the pattern if a charge should be countermined within a few seconds of discharge.

The possible ways in which a hydrostatic firing mechanism may be actuated by a shock wave, and how such actuation may be prevented, are discussed below.

In the first place, the accelerations given to components of the firing mechanism might cause actuation of the mechanism. To overcome this, several methods of rendering the mechanism inertia proof are available, such as: (*a*) mechanically balancing the moving items; (*b*) arranging for the shock to operate an inertia lock to prevent motion of the firing system; (*c*) giving the firing system a natural time period that is long in comparison with the time period of the shock wave; and (*d*) employing a rotary firing system which is immune to axial shocks.

The method employed in British depth charge pistols is none of the above, but an opposed motion device which has proved simple and reliable. This is illustrated diagrammatically in Fig. 57, where it will be seen that to cause the striker to be released, the two pistons must move in opposite directions. This can easily be achieved by the use of hydrostatic pressures, but cannot possibly be caused by acceleration. In the original design there was a central distance piece, but in later designs the distance piece was omitted; this change did not affect firing, but



a *b*

Fig. 57. Sectional View of Firing Mechanism of Depth Charge Pistol

(*a*) In normal position.
(*b*) Striker about to be released.

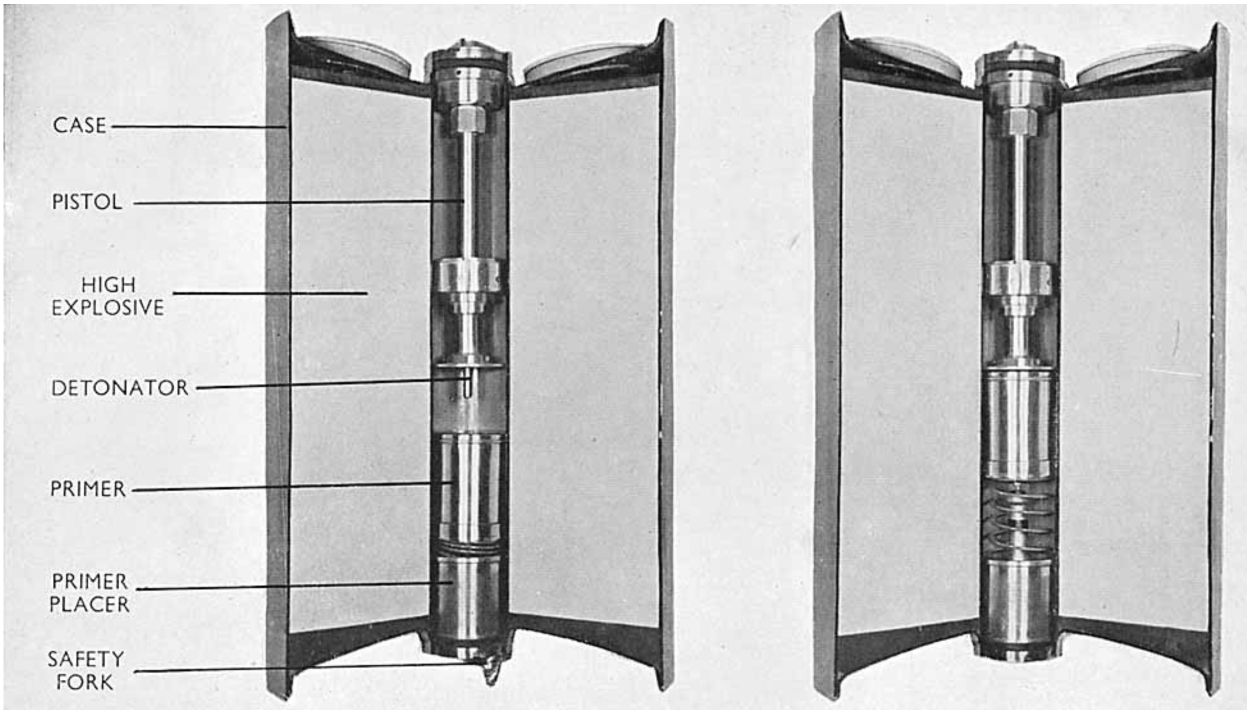


Fig. 37. Sectioned Depth Charge in Safe and Armed Conditions

Fig. 39. Quarter-deck of Depth Charge Fitted Escort Vessel showing Launching Rails, Throwers, and Loading Racks for Depth Charges

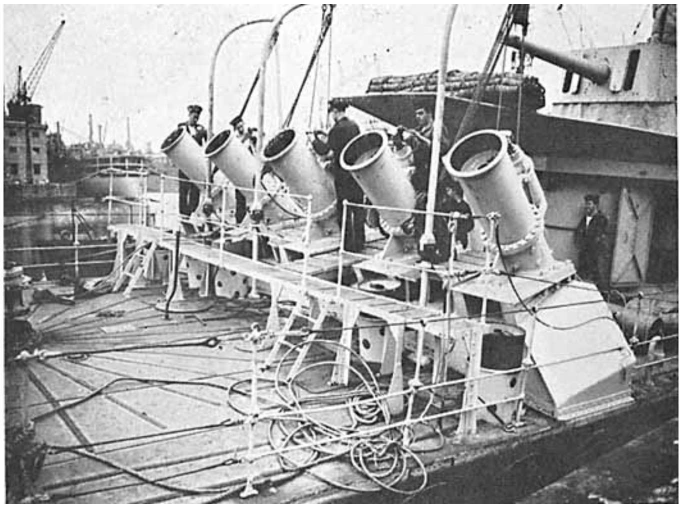


Fig. 43. Battery of Forward Firing Throwers Mounted on Forecastle of H.M.S. *Whitehall*

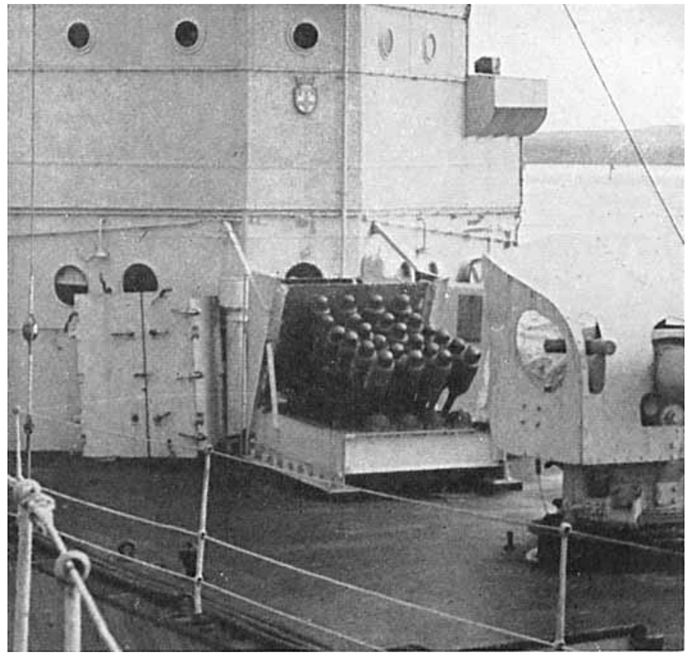


Fig. 44. Hedgehog Mounting just forward of Bridge Structure

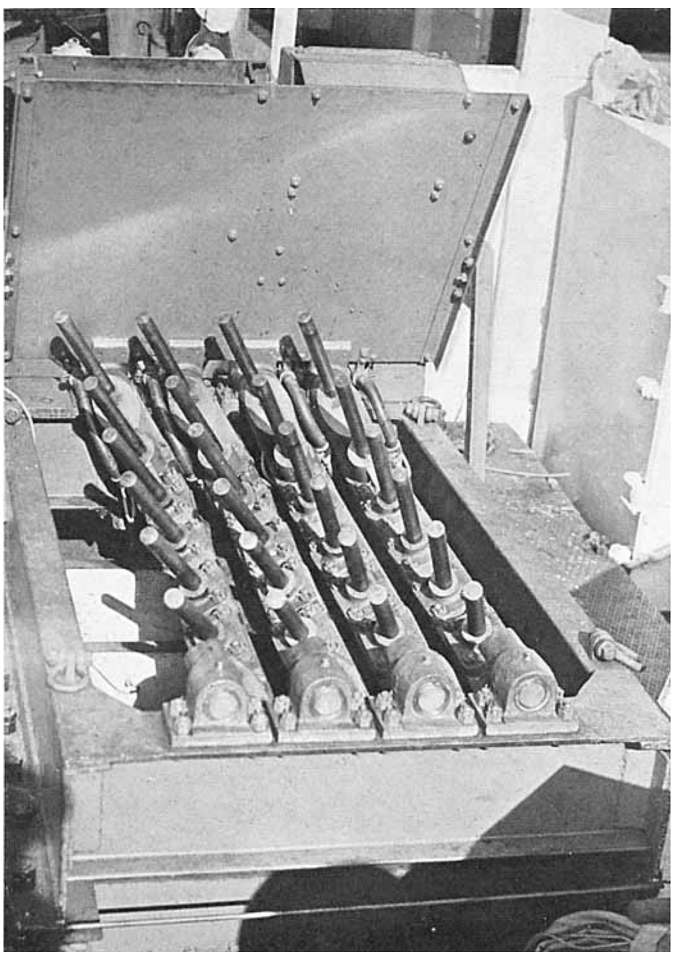


Fig. 53. Hedgehog Mounting trained to Starboard
View taken before end covers were fitted to bearings.

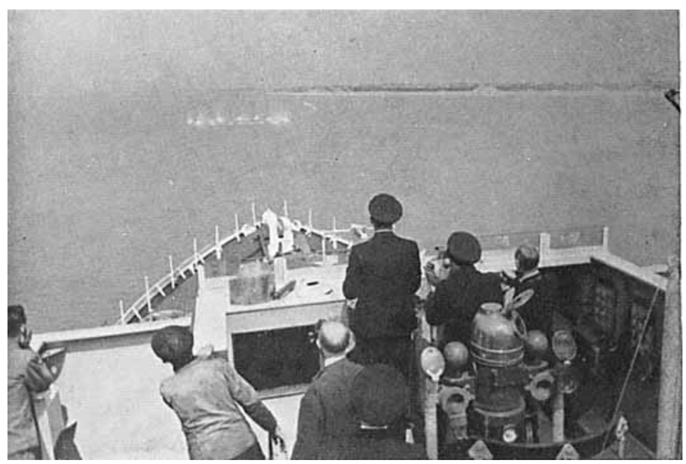
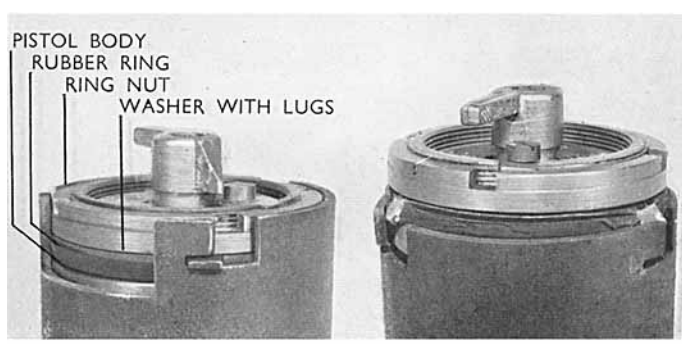


Fig. 45. View of Splashes of Hedgehog Pattern Seen from Ship



a *b*

Fig. 55. Joint between Pistol and Central Tube of Depth Charge
(*a*) View of the joint between pistol and central tube (partly sectioned).
(*b*) View showing pistol in course of being pushed out.

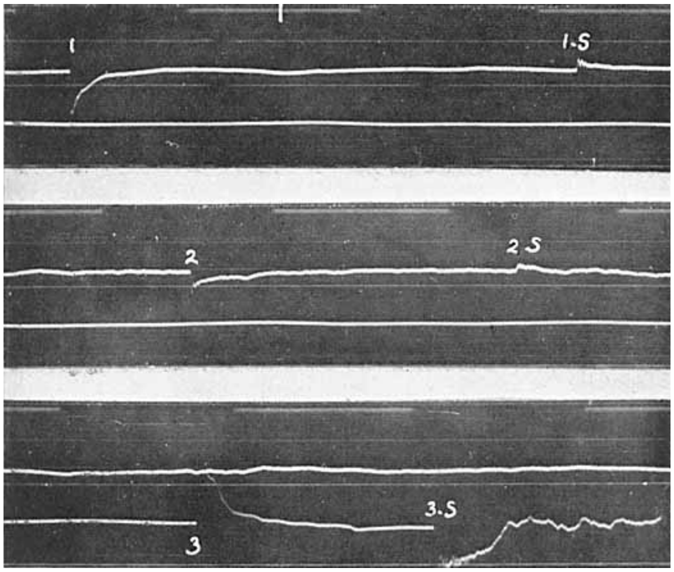
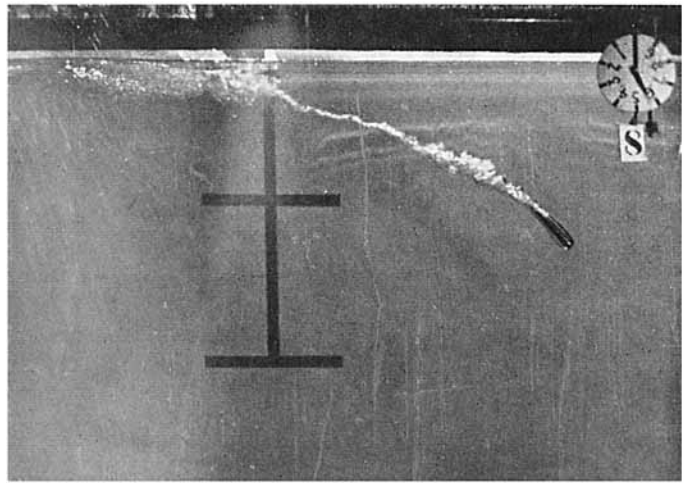
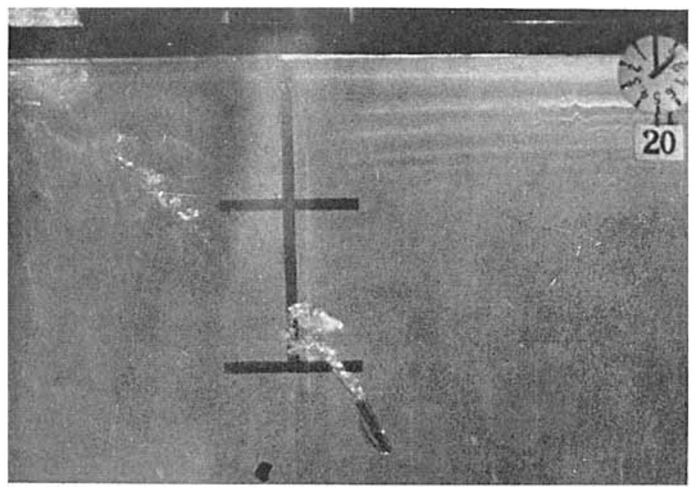


Fig. 61. Typical Record obtained in Sound Ranging for Depth of Explosion

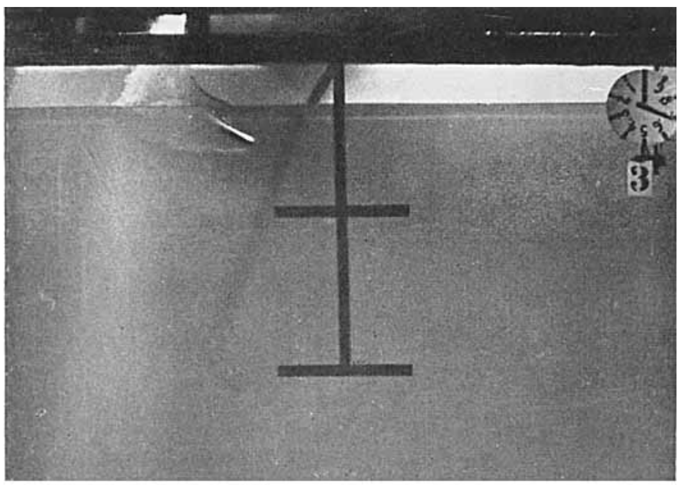


a Entry velocity 235 ft. per sec., entry angle 15 deg., charge at 11 feet depth.

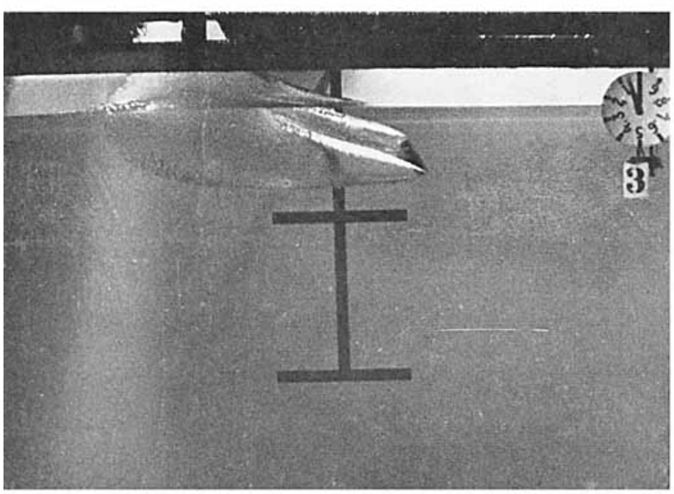


b Entry velocity 235 ft. per sec., entry angle 40 deg., charge at 25 feet depth.

Fig. 62. Depth Charge (Form (*a*) in Fig. 59)



a



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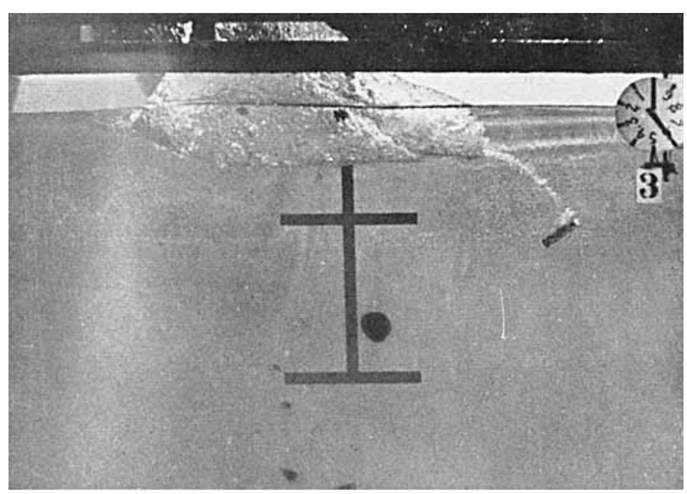


c

Fig. 64. Depth Charge (Forms (*b*) and (*c*) in Fig. 59)

Entry velocity 352 ft. per sec., entry angle 16 deg.

(*a*) Charge at 2 feet depth. (*b*) Charge at 3 feet depth. (*c*) Charge at 9 feet depth. Note that charge is wholly waterborne.

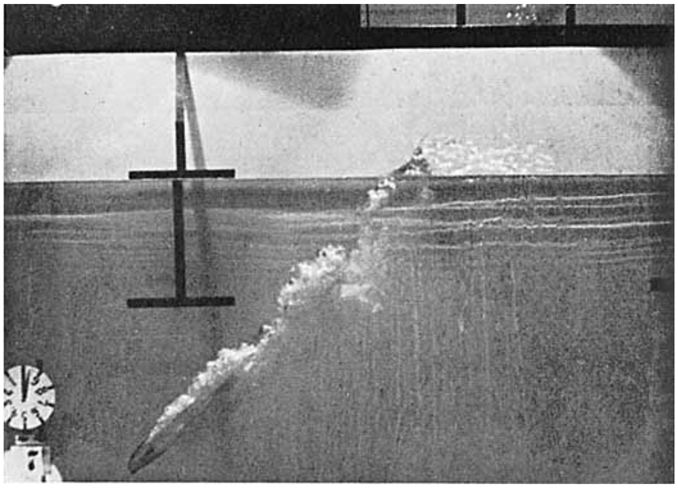
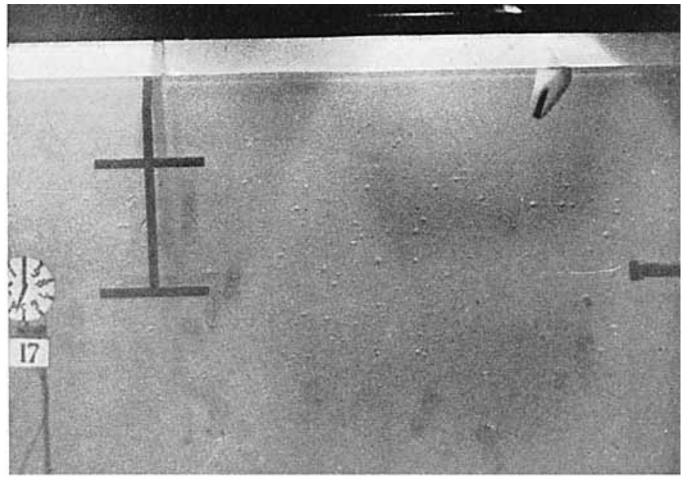
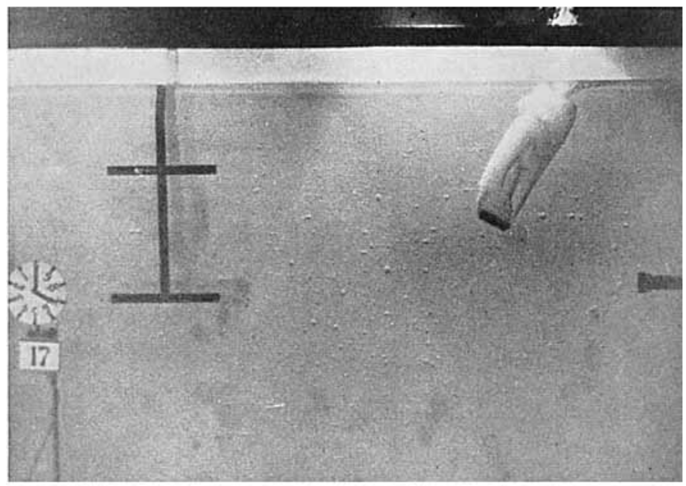


Fig. 66. Depth Charge (Forms (*b*) and (*c*) in Fig. 59)
Entry velocity 400 ft. per sec., entry angle 51 deg., charge at 24 feet depth.

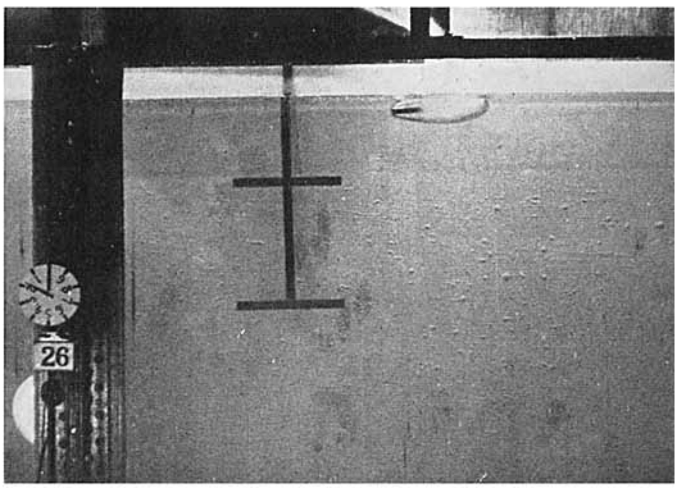


a

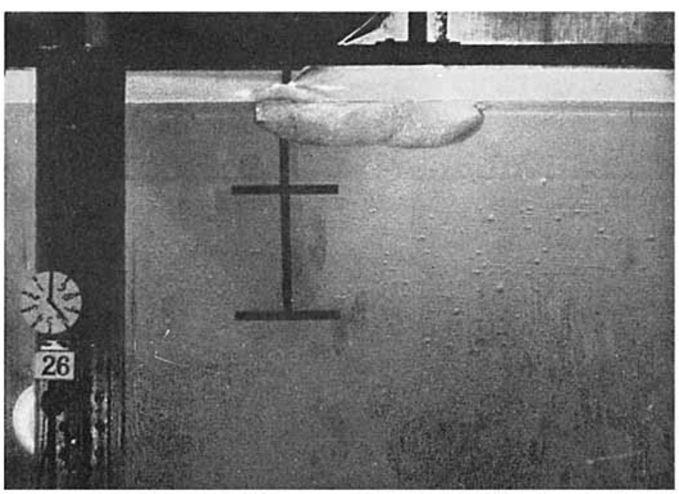


b

Fig. 67. Depth Charge (Form (*d*) in Fig. 59)
Entry velocity 400 ft. per sec., entry angle 53 deg.
(*a*) Charge at 3 feet depth. (*b*) Charge at 12 feet depth.



a



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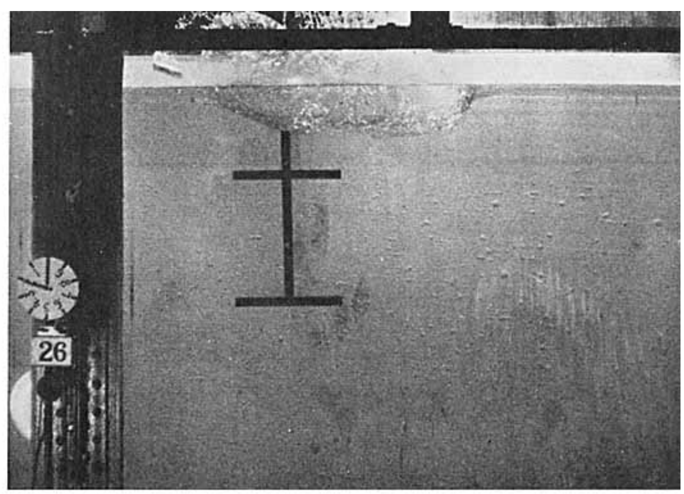


c

Fig. 68. Ricochet of Depth Charge (Form (*d*) in Fig. 59)
Entry velocity 343 ft. per sec., entry angle $7\frac{1}{2}$ deg. Charge leaves water rear end first.

was regarded as improving the inertia proof properties as acceleration would now produce no relative motion of the pistons. A feature of this arrangement is that the spring is only loaded as the two pistons move apart. In the normal condition, therefore, the spring is unstressed, and this avoidance of any stored energy in the system has always been regarded as highly desirable, since in the event of any failure of the ball lock mechanism the striker will not be released under load.

Secondly, a hydrostatic device could be operated by the excess pressure in the water (over that appropriate to the depth) due to the passage of the shock (i.e. pressure) wave. One method of preventing this is to throttle the flow of water to the piston through an orifice, the size of the latter being chosen so that only just sufficient water is admitted to fill passages and piston displacement under the normal pressure-time relationship. This method suffices in the depth charge pistol.

Where this is ineffective, recourse can be made to a flap valve which will close under sudden application of pressure and prevent passage of water until equality of pressure inside and outside the pistol is restored. Such a device has proved necessary when a large orifice has to be employed, due to the total water intake being large in relation to the piston displacement.

It is to be noted that this effect is *additive* in respect of successive shock waves, so that all shock waves of sufficient magnitude must be taken into account; in particular, the wave from the first re-expansion of the gas bubble has been found in some instances to have quite a considerable effect.

A third possible method of firing by countermining is by the transmission of the shock wave through the firing mechanism. It is well known that if a shock wave is transmitted down a bar the returning tension wave cancels the compression wave at half a wavelength from the far end, so that if there is a discontinuity at this point, the end piece will fly off; if the design happened to permit of it, this might cause firing, although no practical example of this method has ever been encountered. As a matter of interest, this effect is used in the Hopkinson–Taylor "pressure bar" to measure the explosive power of small charges by determining the impulse with which the end piece is driven off the end of a bar when the charge is fired in contact with the other end of the bar.

SAFETY REQUIREMENTS

An important aspect of design is that of making the weapon safe to handle. As a statement, this may savour of the obvious, but its implications come perhaps as something of a surprise to an engineer new to weapon design who is not unnaturally prone to concentrate on the method of making the firing device operate. The possible appalling consequences if the weapon should go off in unintended circumstances when stowed in ammunition dumps or on board ship need no emphasis (the explosion of some 2,000 tons of high explosives on a ship in Halifax, Nova Scotia, in 1917 may be remembered), but the effect on morale or fighting efficiency if a single weapon should explode prematurely when being handled is also a serious matter.

The difficulty in dealing with the safety requirements lies in their negative character. To design a weapon to fire in certain circumstances may be technically difficult, but the objective is clear and well defined. The design, however, must also be such that it will only fire under the required conditions and not in any other, and the problem that faces the designer is to try to imagine all the possible circumstances which might cause the weapon to explode, and then to take steps to make the design proof against such occurrences.

The nature and extent of the problem can be seen by an examination of the circumstances under which weapons of the type under consideration might explode prematurely: faulty assembly of firing mechanism; incorrect drill in handling; fire; nearby explosion; dropping from a height; ship sinking; charge lost overboard; small arms, incendiary, or cannon fire; and bomb splinters or bomb blast. How these requirements are catered for varies from weapon to weapon, and no one technique will meet them all. It will not be possible to give examples of the effect of each type of hazard and how it is countered, but the basic principles should emerge from the following considerations.

Since the hazard is entirely due to the presence of explosives, it is necessary to say a few words on the subject of the explosives used in armaments. For this purpose, the explosives used may be divided into three categories; high explosives, intermediary explosives, and primary explosives. High explosives, of which T.N.T. is the most notable example, form the main charge of the weapon, and are chosen—amongst other properties—for a high degree of insensitivity of friction, shock, and bullet or fragment impact. So insensitive are they that they can only be caused to detonate by firing in intimate contact with them a smaller charge of a more sensitive explosive, termed an intermediary explosive. This explosive is itself initiated by the detonator, which contains the primary explosive, i.e. a comparatively sensitive explosive that will develop its full violence from some form of percussion or electrical ignition. Thus there is an explosive train, starting with a few grains of the comparatively sensitive primary explosive and terminating in large quantities of a relatively insensitive high explosive.

The detonator is clearly the weak link in this chain, since if it should explode accidentally—due to some chemical instability in its contents, or some defect or mishandling of the firing mechanism, or to the transmission through it of a heavy shock wave—the whole charge will be detonated; the essence of safety requirements is therefore to isolate the detonator in such a way that if it should explode prematurely, it will not set off the whole train.

While the detonator is isolated, the weapon is said to be safe; when the explosive train is complete, the weapon is said to be armed. The aim of the designer is to arrange that arming will occur only when the weapon is discharged intentionally against the enemy, and not in any other possible circumstances. To do this he tries to utilize some feature of the weapon's performance that will only occur in action. For example, a depth charge has to be submerged to a definite depth before it is required to explode, so that it would be natural to require hydrostatic pressure to cause arming. A depth charge in a sinking ship will, however, be subject to hydrostatic pressure, so some additional characteristic must be sought—for example, that it must have been discharged from the ship.

The method of isolating the detonator in the depth charge is to withdraw the primer away from it; the primer is shown in the safe or withdrawn position in Fig. 37, and it is held in this position by the safety fork against the action of a spring. The safety fork is secured by a lanyard to some part of the ship so that, when the depth charge is discharged, the fork is withdrawn and the spring places the primer over the detonator.

Even this arrangement, however, was not proof against the following actual occurrence during the 1939–45 war. A destroyer steamed into an anchorage, and when she was all but stationary the Captain ordered "Let go", meaning the anchor; but someone "let go" a depth charge, which duly exploded at 50 feet with disastrous consequences.

The firing mechanism for the Hedgehog projectile, referred to earlier, provides an example of how an explosive train is held broken until the weapon has been armed by the correct sequence of events. As shown in Fig. 58, the detonator is mounted in the shutter B which is normally held in the offset position shown in Section XX against the action of the spring C by the striker D. In this position it will be seen that the striker cannot possibly touch the detonator, nor if the detonator explodes due to any reason can it initiate the fire channel E leading to the magazine F.

To cause the striker to be retracted so that the shutter can spring to the armed position (i.e. to bring the detonator co-axial with striker and fire channel) requires the mechanism to have gone through the stages of arming which are: on discharge from the spigot the acceleration causes the collar G to set back against the resistance of the shear pin H (the safety pin being assumed to have been withdrawn earlier); this action unlocks the propeller spindle. On striking the water the propeller is forced to revolve against the resistance of the shear pin K, thereby causing the spindle L to unscrew to the limit of its travel; the spring M then lifts the firing unit so that it occupies the position shown in the scrap view, thus arming the device. If the projectile now strikes a hard object the tumbler N sets forward or sideways, carrying the striker with it against the resistance of the spring O until the ball release operates and the striker is freed to spring forward and hit the detonator.

It will be seen that for the mechanism to become armed it has had to sustain, first, the necessary acceleration on discharge and, second, the necessary speed through the water. If either of these conditions are absent, or if they occur in the wrong order, or if the values of acceleration or velocity are less than the necessary minima, arming cannot take place, and the device will remain safe.

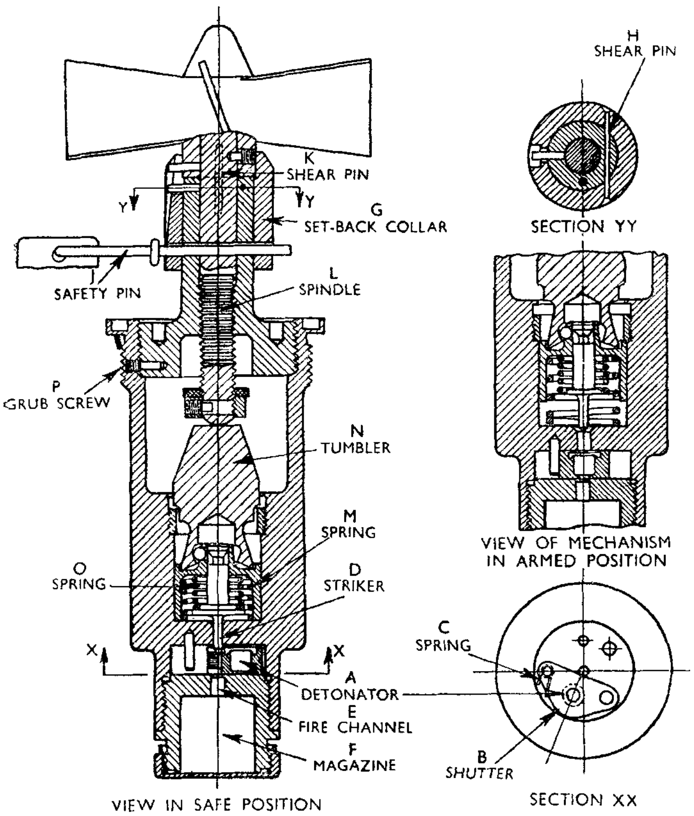


Fig. 58. Sectioned Drawing of Firing Mechanism of Hedgehog Projectile

It is difficult to imagine a more accident-proof sequence of events for arming such a projectile than requiring it first to sustain the necessary discharge acceleration, and then the hydrodynamic pressure (or its equivalent in velocity) consequent upon the initial water entry conditions. It is not always convenient, however, to mount the firing device in the head of the weapon where advantage can be taken of the hydrodynamic pressure or velocity, and in the development of another form of weapon of this general type, it was proposed to substitute for this second stage, the requirement that the weapon should sustain the minimum axial deceleration that would arise from impact with the water when the projectile was fired to the correct range.

It might well be argued that the chance of the combination of inertia shocks having the correct sequence, direction, and minimum values necessary to accomplish arming, occurring accidentally, would be so negligible as to provide an adequate degree of safety. But it can equally well be argued that the weapon *could* be dropped in such a way as to provide the conditions requisite for arming. It does not need further explanation for it to be clear that there is no finality in this type of argument, and that there needs to be the closest liaison and understanding between the designer and user to ensure that the safety of the final product is acceptable to the latter. More than one useful and clever device has failed to find acceptance through lack of appreciation of these safety principles by designers outside the naval orbit.

The firing device for the Hedgehog projectile provides, as it happens, an interesting example of how a designer can be trapped into a false sense of security in relation to the safety of a design. In the original form of this device, the screw thread between the cover and the body was locked by stabbing the thread, and the grub screw P was not provided. If the threads were inadequately stabbed—and experience both in this and in other components suggests that it is easier to give the appearance of stabbing without actually locking the thread than one might suppose—or if a careless person attempted to remove the fuze from the projectile by applying a spanner to the *cover*, the latter can become unscrewed relative to the body, and if this is continued far enough, it will be seen that the striker may be retracted sufficiently to permit the shutter to move to the armed position. It would then be possible for the cover to be restored to its original position without anyone being aware that the safety feature was now completely absent, and it was to obviate this possibility that the grub screw was introduced.

That the dangers arising from such hazards as fire or the explosions of torpedoes and bombs are very real will probably not be disputed, but the possibility of dangers arising from foolishness or carelessness may seem too remote to justify the safety features intended to prevent them. It is seldom that an incident occurs to show how justified all the safety features are, but one that can be mentioned occurred in New York harbour. A salvo of Hedgehog projectiles was fired accidentally from an escort vessel moored at the quay side, and the weapons landed on the concrete surface of the quay and did not explode—a tribute to the safety of the firing mechanism, and also to the shock-proof quality of the explosive.

To conclude this section, an example of an unusual type of safety requirement is to be found in the aircraft depth charge. The arming of airborne weapons is usually initiated by the automatic removal of a safety clip in the dropping away of the weapon as it leaves the aircraft; but in the case of aircraft operating from carriers such a procedure is fraught with danger, for if the weapon is torn off the aircraft by a crash-landing on the carrier or the sea it is likely to become armed in the process, and if actuated by hydrostatic pressure will fire on reaching its set depth. Some method of arming the aircraft depth charge was called for which could not be operated by a crash, and this was achieved by designing the pistol so that its safety clip could only be removed by firing a small explosive cartridge operated electrically from a source of supply on the aircraft under the pilot's control. So long as the pilot's switch remained open, the charge could not become armed in any circumstances.

DEPTH CHARGES FROM AIRCRAFT

Many forms of underwater weapons have the initial part of their trajectory through the atmosphere, and when they finally enter the water may do so at considerable velocities and at a wide range of angles. Study of the behaviour of the weapon in its passages through the air-water surface, and in the early stages of the underwater path, has therefore become essential. Considerable research has been devoted to such studies recently, and the subject has become known as hydro-ballistics. The development of the form of depth charge used from aircraft provides an example of a qualitative form of analysis used in these researches.

Early in the war a depth charge was designed specifically for use from aircraft. The form was adapted from the ship-borne depth charge, the diameter being restricted to 11 inches and the overall weight to 250 lb. to comply with aircraft limitations. This resulted in a charge case 39 inches long carrying 165 lb. of explosive, a hydrostatically operated pistol being fitted in the after-end (see Fig. 59(*a*)). A tail was added to give a measure of aerodynamic stability, this tail being originally a plain open-ended cylinder though this was later changed to one of the drum-and-fin type.

The technical interest in this simple weapon centres round the difficulty that was encountered of getting it to fire at a depth of approximately 20 feet. Early in the war it was anticipated that a submarine, on sighting an aircraft, would immediately dive, and the shallowest firing depth called for was 50 feet—a requirement that created no difficulty. It became apparent as the war progressed that the probability of making a successful attack on a submarine that had submerged was very remote, but that opportunities for surprise attacks on surfaced submarines were sufficiently frequent to make this by far the most promising method of attack; location of submarines by airborne radar naturally assisted in providing the opportunities.

For an attack on a surfaced submarine, the charges must explode at a depth of about 15–25 feet, and the first and obvious step was taken of reducing the hydrostatic firing head of the pistol to 20 feet. Trials showed, however, that the explosions were not taking place shallower than about 35 feet.

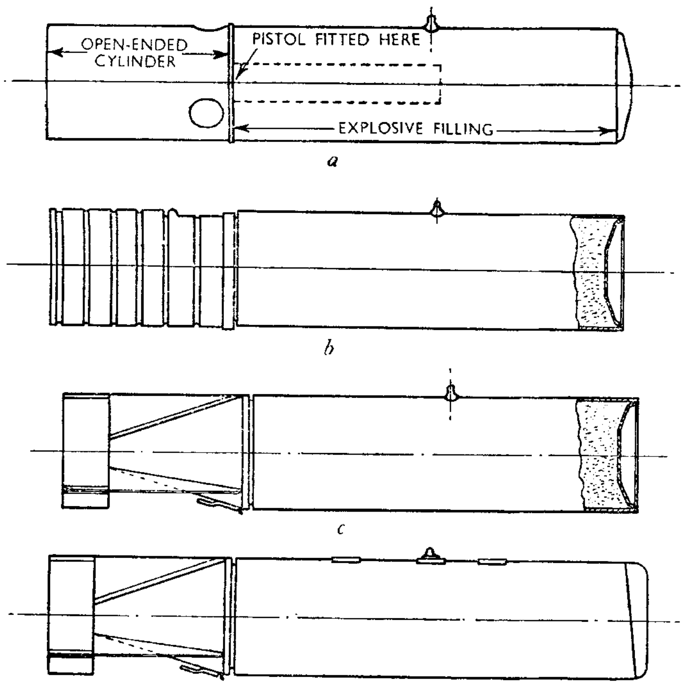


Fig. 59. Stages in the Development of Aircraft Depth Charge

(*a*) Original form with fixed tail.
(*b*) As modified for shallow firing with concave nose and break-off tail.
(*c*) Same as (*b*) but with drum and fin type break-off tail.
(*d*) Form with 5 deg. skew nose and plastic nose fairing; break-off tail as before.

Method of Determining Firing Depth in Open Water. The method of determining the depth at which a charge fires underwater is worth more than passing mention. A sound-ranging technique is used, the instant of arrival of the pressure wave at any point underwater being determined by allowing the wave to impinge on a gauge in which are mounted crystals of a piezo-electric material (i.e. a substance which produces an electromotive force between opposite faces when subjected to pressure); the material commonly used is tourmaline. The arrangement that has been found most satisfactory for the particular purpose of determining the explosion depth accurately is to employ three gauges approximately in line with the explosion. The gauges are slung from buoys, their depth of immersion being accurately known; the buoys are kept at fixed distances apart by a taut wire method, though it is not necessary to know these distances, nor is it necessary for the buoys (and gauges) to be accurately in line.

The electric signals suitably amplified are recorded on two beams of a cathode ray oscillograph, the movement of the beams being recorded on film strip running at 8 ft. per sec., the time scale being provided from a 50 cycles per sec. electrically driven tuning fork, operating a mercury vapour flashing lamp. Three systems of waves from the explosion can reach each gauge—those arriving directly, those arriving by reflection from the surface, and those arriving by reflection from the bottom. The latter (if present) are ignored, and from the time differences between the arrival of each of the two remaining systems at the gauges and the known speed of sound of water, it is possible from simple trigonometrical considerations to arrive at the depth of the sound-source. With suitable precautions, it is possible to measure the depth to an accuracy of ± 2 feet under good weather conditions.

The normal method is to anchor the gauge system to prevent it being carried away by wind and tide, and for the charges to be dropped as nearly as possible on a prolongation of the axis of the gauge line, as shown in Fig. 60. From what has been said, however, it will be seen that a fixed system is not essential, and on occasion it may be convenient to let the whole system drift.

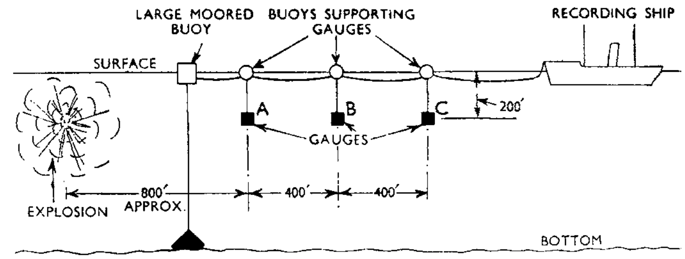


Fig. 60. Layout of Arrangements for Recording Depth of Explosion (not to Scale)

Part of a typical record is shown in Fig. 61, Plate 7; three sections, each showing the arrival of the direct and reflected waves at each gauge, have been cut from a single record so as to bring the total length within a reasonable compass. Gauges 1 and 2 record on upper trace; gauge 3 on lower trace. The symbols 1 and 1·S mark the arrival of the direct and surface-reflected waves for gauge 1—similarly for the other gauges. The oscillatory form of the reflected traces is due to multiple reflections from the surface waves.

Use of Experiments on Models. To discover the reason for the failure to fire shallow, an investigation of the behaviour of the depth charge during its underwater travel was put in hand by the Admiralty Research Laboratory at Teddington. A model of the depth charge 1/11 full size (i.e. 1-inch diameter) was fired from an air-gun into a tank of which the wall parallel to the plane of the trajectory was made of glass. The motion of the model was followed by a ciné-camera, and the film could subsequently be studied frame-by-frame at leisure.

In the study of phenomena on model scale, it is necessary to apply the correct scaling laws if the results are to be reliably interpreted. In these experiments, Froude's law of gravitational similitude has been employed, i.e. the velocity (and therefore the time) is proportional to the square root of the linear scale. For strict scaling the pressure should also have been reduced, but this would have necessitated enclosing the space over the tank and maintaining a reduced pressure therein; for speed and simplicity it was considered satisfactory to operate at atmospheric pressure, as the results would be adequate to provide a good qualitative idea of the sequence of events. In the illustrations and text, all results are referred to full-scale measurements.

The model of the depth charge was fired into the water at a speed of 235 ft. per sec. and at angles of 15 deg. and 40 deg. to the horizontal. Fig. 62, Plate 7, shows how the charge pursues a prolongation of its air trajectory, remaining quite stable, and carries down with it a considerable air cavity. The pressure in this cavity once it has become sealed off from the atmosphere is a matter of conjecture, but it is certainly less than that corresponding to the depth of water. There is clearly no hope of the charge firing until the cavity has dispersed or the pressure in it has reached a head of 20 feet. As showing how persistent such a cavity can be, full-scale trials with a very similar charge fitted with a pistol firing hydrostatically at 15 feet showed that the actual firing depth was consistently about 80 feet deep.

One solution of the difficulty would have been to have fitted the pistol in the nose of the charge, but there were objections to this course. An alternative was to try and cause the charge to depart from its stable attitude. The stable attitude of a uniform cylinder moving through a fluid is with its axis perpendicular to the direction of motion, so if the charge could be displaced from its attitude of neutral equilibrium (axis parallel to direction of motion), it would continue to turn until in the broadside position. This involved two requirements—the removal of the stabilizing tail, and the initial displacement of the axis. The former was met by weakening the rivets securing the tail so that the inertia of the tail due to impact of the charge with the water caused the rivets to shear and the tail to break off; for the latter, the depth charge was provided with a concave nose so that, as the nose passed through the water surface—as illustrated in Fig. 63—the momentary asymmetrical force initiated the desired overturning action.

How completely these alterations modified the underwater trajectory can be seen from a study of Fig. 64, Plate 7. Since all the frames of the film cannot conveniently be shown, Fig. 65 serves as a running commentary on the trajectory. The promise contained in these experiments was reflected in full-scale trials,

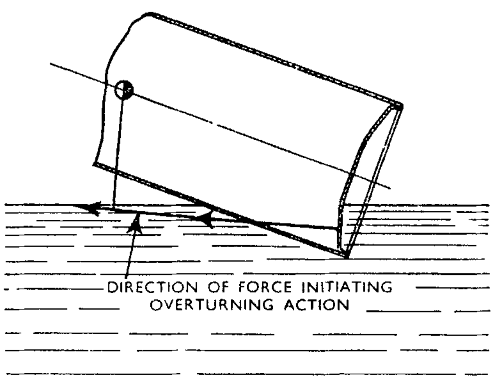


Fig. 63. Diagram showing Non-axial Force on Charge as Nose passes through Water Surface

the charge firing consistently within a few feet of the static firing head of the pistol. The depth charge in this form (see Fig. 59(*b*) and (*c*)) was first issued to Coastal Command of the R.A.F. and to the Fleet Air Arm in 1942, and it continued as the principal airborne anti-submarine weapon for the rest of the war, some 170 German U-boats being sunk by its use.

This satisfactory performance was found, however, to be dependent on a small angle of entry; at large angles of entry, the asymmetrical force at water-entry was of too short duration to initiate the overturning motion (see Fig. 66, Plate 8) and shallow firing proved unreliable. It became necessary, however, to cater for larger angles of entry, since aircraft were being forced to fly higher during attacks to avoid close-range anti-aircraft fire from the U-boats. Now attacks from a greater height demanded an improvement in the air-ballistics, since aiming by eye (as was done for low height attacks) could no longer be relied on. The improved air-ballistics could be obtained by fairing the nose, the addition of 1¼ inches radius on the nose being sufficient to reduce the drag-coefficient from its former value of 0·8 to about 0·22. This clearly conflicted with the underwater requirements, so the fairing was added in the form of a plastic cap which would shatter on impact with the water. To initiate the overturning motion, it was found after several experiments that an excellent performance could be obtained with a flat nose set at 85 deg. to the axis. Fig. 67, Plate 8, shows how rapidly the charge is turned underwater.

There was some anxiety as to whether this form of nose might lead to ricochet at shallow angles of entry if the charge rotated 180 deg. during flight. Trials showed that ricochet was only liable to occur at entry angles less than 10 deg., Fig. 68, Plate 8,

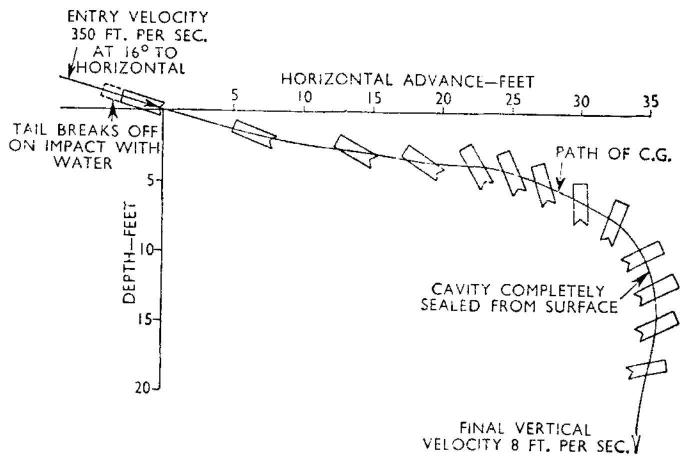


Fig. 65. Diagram showing Underwater Behaviour of Depth Charge Dropped from Aircraft

Leading face of depth charge is concave and tail breaks off on impact with water.

showing a ricochet occurring at an entry angle of 7½ deg. To limit the occurrence of ricochets, it was proposed that the height of the aircraft should not be less than 200 feet, the entry angle corresponding to 200 knots then being 18 deg.

Full-scale trials with this form (Fig. 59(*d*)) showed that, when dropped from an aircraft flying at 120 knots and 1,500 feet (entry velocity 350 ft. per sec.; entry angle 60 deg. to horizontal), the firing depth was 20±4 feet when a pistol having a static firing head of 16–17 feet was fitted. By the time these trials were complete, however, the Germans had withdrawn their U-boats and fitted them with the "Schnorkel" which altered completely the form of aircraft versus submarine warfare.

Acknowledgement. The author wishes to express his thanks to the Admiralty for permission to publish this paper.

Discussion

Mr. O. Thornycroft, O.B.E., B.A., M.I.Mech.E., said that the time saved by employing small-scale models to help in the design of underwater projectiles had been abundantly proved during the 1939–45 war when speed in the development of new weapons had been vitally important.

The results of underwater projectile scale-model trials usually agreed well with the final full-scale results: the sinking speed of a "stable" projectile (one that did not turn sideways) calculated from drag measurements taken in the compressed-air tunnel at the National Physical Laboratory (N.P.L.) agreed within 5 per cent with the results obtained by sea trials. Mr. Kirkby had described how measurements of underwater velocity and depth had been made at sea by acoustic methods. The sea trials with which the wind-tunnel tests were compared had been carried out in the same manner. By employing the N.P.L. compressed-air tunnel and a full-scale model, the Reynolds number could be increased up to and even above that corresponding to underwater conditions in service. The Reynolds number range concerned lay between 10 and 30 millions.

In the pitch and yaw of a projectile, the stabilizing moments would have been difficult to measure by full-scale experiments in water; two model methods were employed, and the agreement was unexpectedly good. A small-scale model in a water tunnel gave results that differed by less than 4 per cent from the results obtained at full-scale Reynolds number in the compressed-air tunnel. There was a wide difference of Reynolds number, but that appeared to be of less importance in measuring moments than in the measurements of drag.

During the 1939–45 war, invaluable assistance in developing underwater projectiles had been given by the N.P.L. with models in the compressed-air tunnel. The experiments were closely co-ordinated with small-model trials in the water tank at the

Admiralty Research Laboratory. In certain cases model experiments in a water cavitation tunnel were made concurrently, all being directed to the development of a single type of underwater projectile.

Mr. STUART MIALL, A.M.I.Mech.E., said that, in 1940, a mine was required that would be effective against shallow-draught vessels at all states of the tide. An antenna mine in which the upper antenna floated had been conceived, but was not very practical. Any ordinary stranded wire, particularly if it had been rolled on a drum, had acquired a permanent set, and when it floated freely in water (supported by little floats) it coiled up into a rather tight tangle, so that 60–70 feet of it occupied very little space, afforded small protection against enemy invasion craft, and was very conspicuous from the deck of a ship.

A wire with some self-straightening properties was required, and he had tried expanding curtain rod—a single wire wound into a close-coiled helix—in conjunction with little wooden floats. It had worked extremely well, the dummy antenna straightening out in still water.

A firm in the Midlands were prepared to make this close-coiled helix, using (necessarily) bronze wire, and arrangements for stowing and releasing were schemed out. The electrical department reported, however, that the resistance of the single-strand helical wire was too high, because the current flowed round the helix and not across the coils, and the firm were asked whether they could make a wire containing five or six strands in parallel. They succeeded in doing that, threading together, by hand, a number of open-coil helices, though not without initial difficulties.

The five-strand wire was very much stiffer than single-strand wire, and the stowage and release mechanism had to be re-designed. The original container had been about 1 foot in diameter; in the final solution (Fig. 69, Plate 9) it was about 3 feet.

The floats were made with grooves top and bottom, so that the wire could nestle neatly into them, giving a canister of the minimum depth. They were not equally spaced along the wire; there were two long intervals followed by a short right round. The twenty-four floats ultimately filled up the entire space round the trough, and in no place was the wire in shear between neighbouring floats. Advantage was taken of the elasticity of the wire, so that the eight turns of antenna with floats were squeezed into a depth of 5 inches.

The method of release was shown in Fig. 69. The little hinged flaps were counter-weighted at the inner end and held down by spring clips at the outer end. A band encircled the trough, and when the band was released the springs flew out and the little hinged flaps were free to lift up. The floats lifted the antenna out of its trough. The net buoyancy of the whole arrangement was under 2 lb., so that it had to be quite frictionless to prevent the antenna's sticking in the container, and, perhaps, the mine's being fired as soon as it was armed by the safety switch. The two ends of the spring-retaining band passed over a small tab on the outer wall of the trough. They were held against the wall of the trough by a plunger, and the plunger in turn was held against the band by a soluble plug, which dissolved after being so many minutes in the water. When the plug had gone, the plunger was withdrawn by a spring; the band flew clear; the springs flew out; the flaps lifted, and the antenna floated free, and even in still water it quickly assumed a straight form on the surface of the water, extending to about 60 feet.

The mines had later been used as an anti-submarine measure, and he wondered whether they had sunk any submarines.

Mr. H. E. SHARP, M.I.Mech.E., said that the depth-charge thrower illustrated in Figs. 48 and 49 was fitted with arrangements for arresting the tray and piston which carried the depth charge. The original depth-charge thrower was not so fitted, and in consequence the tray and piston were lost each time the weapon was fired. The saving in material, labour, and stowage space on board ship, together with the reduction in loading time, fully justified the change to the more complex design.

An interesting shock effect was experienced during the development of the arrestor gear. The two arrestor cylinders shown in Fig. 49 were connected by a pipe to ensure equal pressures in the two cylinders. This pipe was made of steel, $\frac{1}{4}$-inch bore and $\frac{9}{16}$-inch outside diameter, and it was capable of withstanding an initial pressure of at least 30,000 lb. per sq. in. The pressure built up in the cylinders during the arresting stroke was only 5,500 lb. per sq. in., and yet, on two or three occasions when a proof round was fired, an equalizing pipe was split longitudinally for a length of 2 or 3 inches. The pipe material was exceedingly good with regard both to ultimate strength and ductility. The pressure reached by the liquid in the pipe was shown by measurement to attain from 10,000 to 28,000 lb. per sq. in., and the equalizing pipes used in the trials withstood those pressures, with no apparent sign of excessive stress; the trials indicated, however, that pressures far in excess of the cylinder pressure could be produced in the equalizing pipe.

It was thought that at the instant the piston entered the arresting cylinder a pressure of 5,500 lb. per sq. in. was built up in less than 1 millisecond, and pressure waves, produced almost simultaneously in the two arrestor cylinders, occasionally met in the equalizing pipe, the wave energy being absorbed mainly in stretching the pipe at the point where the waves met, and, with so small a volume of metal to absorb the energy, producing excessive pressures. A restriction plug of $\frac{1}{8}$-inch bore was therefore fitted on each end of the equalizing pipe to reduce the amount of wave energy entering the pipe, and it proved to be a complete cure.

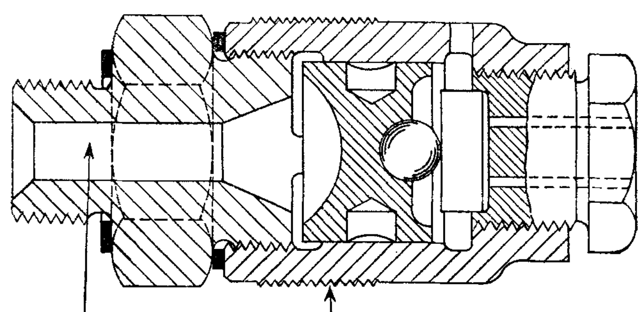


Fig. 70. "Brinell-type" Pressure Gauge

The apparatus (Fig. 70) used to measure high but transient pressures had been designed originally for measuring the maximum pressures reached in cartridge containers; in it the pressures were estimated by the diameter of the indentation made by a standard 10 mm. steel ball in an annealed mild-steel disk. The steel ball was supported by a light-weight piston acted on by the pressure to be measured. The piston was lightened by having holes drilled in it, and the space behind the plunger was filled with grease, to prevent the ingress of dirt or grit which might cause the piston to seize in its housing. The steel used for the disks was calibrated in a Brinell hardness testing machine, and from the results obtained a curve was plotted relating the diameter of the indentation to the pressure on the piston.

Gauges having pistons of various diameters had been made, covering a pressure range of from 300 to 30,000 lb. per sq. in. The gauges were very robust and simple to use, and they gave consistent results. Calculation indicated that the time required to make an indentation was only a few tenths of a millisecond, and independent pressure measurements made with a cathode-ray apparatus confirmed that the Brinell type of gauge, when correctly designed, gave reliable readings.

Mr. C. W. LONGMAN (Oxford) said that, during the 1939–45 war, his company produced sea-mine hemispheres as cold pressings; previously they had been produced as hot pressings. Their method was satisfactory in large-scale production, although its use was conditioned solely by the equipment available at the time of projected manufacture, and was not necessarily most suitable. The processes might be modified to suit other equipment.

The double-acting, mechanical, crank presses were rather small to produce a hemisphere in two draws, and therefore three draws were used, allowing a margin of safety against overloading. The material was sheet steel purchased from the rolling mill in circular blanks. It was pickled, to remove scale, and was preferably of a basic open-hearth type, a typical specification being: percentage carbon, 0·04–0·1; sulphur, 0·05 maximum; phosphorus, 0·05 maximum; and manganese, 0·5–0·6; with a trace of silicon. The ultimate tensile strength was only 19–22 tons per sq. in., and the yield 13·5 tons per sq. in., with an elongation of 35 per cent from 2 inches. The rather low yield point was needed to give better drawing properties to the sheet, and would not detract from its life, as cold working increased the yield by about 20 per cent.

The most satisfactory blank was considered to be 59 inches in diameter and 0·178 inch thick, and between 130 and 140 lb. in weight. The weight of the finished hemisphere was not to exceed 135 lb. with the large mouth and 140 lb. with the small; the hemispheres produced actually weighed 105 lb. and 115 lb. respectively. The tolerance on thickness was 0·015 inch from sheet to sheet, with a variation of thickness over the surface of each sheet of approximately 0·012 inch.

Fig. 71*a*, Plate 9, showed a blank before and after the first forming operation. The second form very nearly completed the shaping, and a similar die carried out the final operation of sizing the hemisphere to the final dimensions. Fig. 71*b*, Plate 9, showed the finished hemisphere alongside the press and die which produced it. The surplus metal on the skirt was trimmed off by a clipping operation in four quarter turns, as shown in Fig. 71*c*, Plate 9. The mouth was then pierced and flanged in a die, and the edge of the metal was flanged over the ring as in Fig. 71*d*, Plate 9. The finished hemispheres and an intermediate belt were tack-welded together to form a complete mine shell. The final welding operation was made outside the jig, to save time and expense.

Tests were carried out, to determine the strength of the cold-drawn mine, in a tank consisting of a vertical cylinder, the top of which was closed by a domed cover-plate bearing on a rubber seating. There was a compensating device consisting of a plunger which could be loaded at will, with a draining cock and filling pipe at the bottom of the tank. The tank was filled with water at mains pressure; the air release valve on top of the cover-plate was closed, together with the water-main cock, and pressure was applied by a pump, readings being taken from the pressure gauge; any desired pressure could be maintained for duration tests by loading the compensating plunger with weights. A collapse of the mine shell was indicated by an immediate fall in the pressure. The first tests were disappointing, the mine belt failing at a pressure of only 250 lb. per sq. in., usually adjacent to a longitudinal weld in the belt.

Annealing locally along the skirt accounted for the reduction in strength at that point. When the annealing operation was discontinued, the mine belts collapsed in the centre between the two hemispheres, and therefore the thickness of the belt was increased. Pressures between 340 and 380 lb. per sq. in. were then obtained without damage to the belt or adjacent areas.

Hemisphere	Pressure at failure, lb. per sq. in.	Average thickness		
		In blank, inch	After forming, inch	Thinning, inch
1	370	0·200	0·180	0·020
2	325	0·188	0·176	0·012
3	325	0·176	0·170	0·006
4	No failure at 370	0·185	0·162	0·025

Failures then occurred near the mouth aperture, and several types of aperture reinforcement were tried, but without great success, because most of the trouble was caused by variations in the strength of the mine hemisphere pressings, due to slight discrepancies in the cold working (or stretching) of the steel.

Tests carried out on mine shells produced from special hemispheres, carefully gauged for thickness before and after pressing, revealed that the strength of the hemisphere varied with the amount of cold working, and the thinning of the steel in the critical area. The hemisphere thinnest after pressing was the strongest, as shown in the table.

The results of a further series of tests were in agreement with those recorded, except that the pressures were higher. This is attributable to the delay of several months between the time of pressing the hemispheres and its testing, during which time age hardening probably took place. The Admiralty required mine shells to withstand pressures of approximately 375 lb. per sq. in.

Mr. P. Hall (Birmingham) described the production of contact mines by a firm of motor-car manufacturers. The sinker was treated as chassis (Fig. 72*a*, Plate 10) and the mine shell as body (Fig. 72*b*, Plate 10), the two finished components being brought together at a marrying point (Fig. 72*c*, Plate 10) from which, after inspection, the married unit was conveyed to a railway truck.

Hundreds of jigs, tools, and gauges were designed and manufactured for machine tools formerly engaged on automobile components. Assembly lines were prepared, and a sequence of operations was planned on a 5-minute cycle, giving twelve units per hour per line. Test-tank assembly, and inspection fixtures were designed, made, and installed in correct sequence.

Meanwhile, men who had previously been body mounters, wing fitters, and the like, were trained to weld; axle and car assemblers became assemblers of pawling and firing mechanisms; body-makers assembled sinkers and mines shells, and girls from the trimming department turned to the task of making up ring mains and wiring leads. All the inspection and functional tests were carried out by the firm's own staff, under the supervision of the Inspector of Naval Ordnance. Within four months they had produced and despatched their first batch of completed units, scheduled for laying trials. When those had been found satisfactory, full production was commenced, and, after nine months, the target of 1,000 a week was reached; the record week's output, in October 1940, was of 1,248 units. The weight of one unit was about 24 cwt.

Mr. R. P. Bossom (Birmingham) said that his firm undertook the manufacture of the clocks required to render the mines "safe"; a large order was placed at short notice. Clocks of the lever escapement type had not been made to any great extent in Great Britain prior to the war, and his own firm had not engaged in this sort of production. The question of the correct teeth to use was an early difficulty, but they succeeded in getting hobs of the correct type. There was, however, a shortage of hobs and it was impossible to get them from the Continent; a new form of tooth was developed to enable all the various toothed wheels of the same pitch to be cut with one hob. It was known as the "circular arc tooth", and, although it was thought to be new, something very similar was described in the ninth edition of the "Encyclopaedia Britannica". The constants used in the development of the hob form needed a certain amount of alteration, however, but some suitable hobs had been obtained before the Continent became shut off.

The accuracy which was required for the setting of these clocks was fairly high. They were driven by a small dry battery, and had to operate in a certain manner for a considerable time. Eventually they were fairly successful in turning out the clocks to the Admiralty's requirements, though there were teething troubles. Various modifications were made to the design, and a spiral spring was substituted for the original clock spring, greatly simplifying the fitting of that particular component in the clock.

The period delay-device, called a "ship counter" in the paper of Dr. Wadlow's, was somewhat difficult to manufacture to Admiralty specification. It was much harder to start an escapement than to keep it going. In the specification in question, the device was required to start a number of times consecutively without a single failure, and if it failed it was rejected. The escapement had to be specially set to ensure self-starting, as the ordinary lever escapement was not a self-starting device. Various modifications to the apparatus were suggested, and many experiments were carried out, but he did not think that the modified design was adopted by the Admiralty.

An anti-countermining device, consisting of a very delicately arranged arm on a very fine wire, carrying at the end a tiny contact, was made by his firm. In it, a pointed contact pressed against a flat contact, and pitting had to be avoided.

Mr. H. G. LORD (Bath) observed that the conditions in which mines had to be stored and supplied influenced the mechanical aspects of supply. The variety of operational needs and uses had to be matched by an equal flexibility in supply, since mines were sometimes required in large numbers, at short notice. A bewildering variety of types might be entailed, which would make impracticable demands on man-power and storage space.

To overcome that difficulty, the British practice had been to regard the mine shell as merely a container, and to rely on ingenious combinations of a relatively small number of different components to achieve a variety of firing systems. In general, therefore, the manufacture of mine shells and of components were dissociated, and the work of assembly and storage was undertaken at Royal Naval mine depots, manned by civilian staff; the antenna mine of which very large quantities were required, and which entailed no operational change in the circuit, was an exception.

At the mine depots, the problem was affected by the presence of the explosive containers, which prevented the installation of many kinds of machine and the use of many techniques otherwise acceptable. The two conflicting needs of speed and safety, coupled with the shortage of labour under war-time conditions, imposed severe limitations on the designer, and created a host of problems for those responsible for the work of assembly. Continual changes in types of mine, sinker, and firing circuit militated against the adoption in the depots of a mass-production layout, except in special cases. There was also continual evolution of design to meet changed circumstances, or to increase efficiency or safety. The result was a flow of modifications of varying complexity and importance, which complicated the work of preparation, adjustment, and testing.

Perhaps one of the factors which set mining work in a class apart was the impossibility of trying out each final product individually, under service conditions, before issue to the Navy. A mine could not be fired, like a gun, or given a trial run, like a torpedo: it worked only once, and success depended on the quality of the design and workmanship, and the care taken in its preparation.

Mr. E. V. MARCHANT (London) remarked that the carriage of mines in aircraft presented a number of problems. The general external shape was satisfactory but various minor projections and irregularities caused difficulty. It was not safe to rely on drawings of the mine and aircraft: the only way to ensure that the one would fit the other was to make up a dummy model of the mine and try it.

The safety requirements for aircraft mines were very stringent, and with the growing complexity of the mines more than one fusing wire was sometimes necessary to actuate the safety devices. It was not easy to ensure that the pull-off load for these fusing wires was sufficiently great to prevent their accidental removal, and yet not enough to damage the aircraft. There was also a line to open the parachute, and at one time there was alleged to be a danger of a mine, which should have been released, being suspended from the aircraft solely by the parachute line and the fusing wires.

The parachute attachments for British aircraft mines were largely to the designs of the Royal Aircraft Establishment, which worked in close collaboration with the Admiralty Mining Establishment. The essential feature of all designs was that the parachute should be released from the mine on impact with the water. In later designs, the parachute attachment was fitted on to the mine by what was, in effect, a large eight-entry bayonet joint. The diameter was about 18 inches, and several attempts were made before the manufacturing tolerances were satisfactorily defined, and suitable gauges provided, to ensure that the parachute attachments fitted the ring on the end of the mine. The parachutes were supplied separately and had to be fitted on the airfield. With some of the earlier models, interchangeability was by no means certain, and a file was an essential item in the tool-kit.

In preparing stores of that nature for loading on to aircraft, it was desirable to avoid the need for tools as far as possible. Special tools were particularly to be avoided. If a slight criticism might be made of the work of the Admiralty Mining Establishment, it would be that they did not always sufficiently bear that point in mind. At the loading point, a single tool forgotten might cause the armourer to make a journey of several miles to fetch it.

At the beginning of the war, a range of anti-submarine bombs for aircraft use was available. The fusing systems for those bombs provided for either an instantaneous detonation in the event of a dry hit on a submarine, or for detonation after some time-delay if the bomb entered the water. For a variety of reasons, the shortest time-delay which could be provided was $\frac{1}{2}$ second. A high proportion of U-boats attacked from the air were on the surface, and the most accurate attack was that at low level. Such an attack was not possible with the existing anti-submarine bombs, because, in the event of a dry hit, the resulting instantaneous detonation would cause damage to the aircraft dropping the bomb, while, if the bomb entered the water, the $\frac{1}{2}$-second delay caused it to detonate at too great a depth to inflict lethal damage on a surfaced submarine.

That was the position in 1940; and it was to the credit of Taylor's original depth-charge design that it was possible, for a time, to use standard Naval depth charges without any modification whatever for dropping from aircraft: they had not been designed for such severe release conditions.

A considerable amount of model and full-scale work was done at the Royal Aircraft Establishment and at the Marine Aircraft Experimental Establishment of the Ministry of Aircraft Production; the relations between the many departments concerned with the problem of mine design were admirable.

Mr. A. LIGHTBODY, B.Sc., A.M.I.Mech.E., said that the work of air ballistics during the war was done by the Armaments Department of the Royal Aircraft Establishment at Farnborough; the depth charge described by Mr. Kirkby was of special interest to the bomb ballistician. It was originally a plain cylinder with a blunt nose, and its air ballistics were not very satisfactory when it was dropped from a fairly high altitude; at a later date, when it was necessary to increase the height of release of depth charges, owing to more effective anti-aircraft fire, it was necessary to increase the terminal velocity of the missile.

Difficulty was encountered. In the early days a radiused nose was fitted to the depth charge, the radius being of the order of $0{\cdot}07 \times$ the diameter. Dispersion of the store was rather large, and it was discovered that the nose radius was extremely critical. If the radius was much less than $0{\cdot}07 \times$ the diameter, the drag coefficient of the missle was high (about 0·8), whereas if the nose radius was of the order of $0{\cdot}1 \times$ the diameter, or more, the drag coefficient was low (about 0·22). It was very important not to err on the low side; if one did, the drag coefficient was liable to vary considerably during the flight of the bomb, and inconsistent ballistics could result.

Mr. A. STUART WATTS (Doncaster) said that, for the wire mooring ropes, certain conditions had to be met: (1) there had to be a minimum of stretch and elongation; (2) the rope had to be reasonably flexible; (3) a fairly large diameter wire was needed, with protection to delay corrosion; and (4) there should be maximum strength with minimum size. The most desirable construction of rope to meet those demands was of 7×7, with six strands each of seven wires closed over a core of seven wires. The wires were galvanized and drawn to a tensile strength of about 110 tons per sq. in. The type of $1\frac{5}{16}$-inch circumference was required to give a breaking load of about 7·75 tons, and that the 1-inch circumference a breaking load of 4·5 tons.

The periodical endurance tests made in the past revealed that total fracture of mine mooring ropes occurred at a section at or near the mine or sinker, and the cause was traced to an acute bend or to flexing over a small radius. The elimination of those points of small radii, by the provision of sheaves, or of a flexible rubber surround, considerably increased the life of the moorings. Protection to delay corrosion was best provided by good galvanizing with a rope preservative, preferably during manufacture itself.

In war periods, the enormous increase in demand placed a great strain on wire-rope making resources, on the score both of raw material and of available plant. During the 1914–18 war, the emergency was met by the use of a specially made "rope unit" in which a number of fibre strands were run in with the wires; that provided flexibility, while the fibre strands retained lubricant. It also enabled a larger number of machines to be brought into operation; moreover, no closing action was necessary. That unit met the emergency, but was abandoned at the end of that war period.

During the 1939–45 war, galvanizing such a vast quantity of wire of small diameter became a bottle-neck. The problem was solved by the use of drawn galvanized wire. In this process the wire was galvanized, during the drawing stages, at a larger size than the finished gauge required. For example, a wire to finish 0·040 inch in diameter could be galvanized when its diameter was 0·128 inch, and then drawn down to the required final size. That enormously increased the output of the available galvanizing plant, and also enabled heavier galvanizing plant to be brought into operation. Wire galvanized by the hot process and then drawn down to size would not have such a thick coating of zinc as wire hot-galvanized at its finished diameter, but the method enabled huge demands to be met.

Splicing a rope, even to provide a terminal such as an eye, would reduce the rope's tensile strength and provided a section susceptible to corrosive failure when those splices were in or near salt water. Swaged terminals, in place of splicing and white metal socketing, could be made much smaller and more quickly than a spliced end, or even a white metal socket, and yet be as strong as the rope to which they were attached, and their use as attachments or stops on the intermediate portion of the rope had no doubt been the means of solving many awkward problems.

Mr. J. BARYE SWAN (London) said that, in the mass production quantities of mines and accessories partial interchangeability for production in any given maker's works, and full interchangeability of parts and accessories made by many firms and assembled at an assembly plant, had to be considered; proper tolerances were required to be indicated on the drawings.

Mine hemispheres were pressed by two methods in war-time bulk production: a cold process in which the large power presses such as found in the motor-car body-building plants were used, and a hot process which employed the hydraulic flanging and drawing presses common to boiler shops.

The older, hot process of producing mine hemispheres employed plates of $\frac{3}{16}$-inch thickness and more: it was used exclusively for hemispheres of $\frac{1}{4}$-inch thickness, because, for such heavy material, the cold pressing loads were beyond the capacity of the largest presses, without intermediate annealing operations between the draws.

In hot-pressing the $\frac{1}{4}$-inch plate was the easier to raise as it retained the heat longer and remained more plastic. Below $\frac{3}{16}$ inch, a plate was difficult to raise in one operation. A normal type of flanging press was used, with jack rams in addition to the main ram, and drawback rams for preference. Such a press was usually found in a well-equipped boiler shop. The press should be fast working, with large delivery pipes, especially for the thinner material. A push of about 150 tons was required from the main ram, and one of 30 tons on each of the jack rams. *Usually the female die was held on the top, stationary table and* the punch on the moving ram; the pressure plate was fixed to the jack rams and held by them during pressing: correct spacing was maintained by a mild-steel ring around the outer periphery of the pressure plate. Dies were ordinarily of a good quality grey cast iron, a mild-steel ring being fitted in the mouth of the female die, at which point the radius was important and the surface had to be kept as smooth as possible; maximum wear took place there, but the ring could easily be renewed when scored and worn. The material used is a light boiler plate similar to B.S.I. 14, but specially rolled to a close tolerance of +12 per cent of the nominal plate thickness. That tolerance covered variations over any one plate and from plate to plate; torn hemispheres and sticking in the dies could result, with serious delays in production, if the tolerance was not maintained.

A standard type of furnace was used for heating plates in an initial batch of about eight. The plates took 10 minutes to heat up, and about 20 seconds to form into a hemisphere—the quicker, the better, because serious corrugations were formed round the equator (and led to welding difficulties) if the plate became too cold. To form a hemisphere took about $1\frac{1}{2}$ minutes, from removal of the plate from the furnace to setting aside to cool. Whenever a plate was removed from the furnace, a fresh plate was put in, so that a continuous flow was available at 2-minute intervals.

The female die was water-cooled and the male die was cooled by air blast and washing with graphite and water between operations; that enabled a good dimensional control of the pressing to be maintained. The remaining operations were not unusual. The hole was cut out, by a motor-driven gas torch, from a centre marked by the male die during the pressing process. The neck was raised hot; the spinning was done cold; and the final trimming at the equator was by a motor-driven torch running on a platform in the plane of the equator, while the hemisphere was seated in a suitable jig.

The belt joining the two hemispheres to form the complete mine shell was in some cases barrel formed, and joggled so as to lap for about $\frac{5}{8}$ inch inside the hemispheres. That type of belt formed the strongest mine shell, though not until a suitable manufacturing process had been schemed out. The belt was rolled to the joggled barrel section and formed to a circle at the same time. The joint was then flash welded, trimmed, and cold stretched about 1 inch, to size. That gave close dimensional control and at the time produced a true geometric form which reduced the tendency to secondary failure.

Straight belts lapped inside the hemisphere were tried at one time and always failed by crushing at a lower load than a butt-welded belt, owing to the non-axial load and the external pressure acting to produce the same deflexion. A straight belt lapped outside increased the failing load by some 70 per cent, the non-axial load produced a deflexion opposing that which external pressure tended to induce.

In the hot process, automatic arc-welding was frequently used and gave very satisfactory results. Union-melt submerged arc was sometimes used, but was rather difficult to keep on the seam: the arc was invisible and needed experienced operators.

Jig welding was used a good deal in mine-sinker production, and, by suitable design of jigs, close dimensional control was achieved.

The sides of the sinker were blanked out and all the necessary holes were pierced in them; they were then held in a suitable jig and arc-welded by hand. The bottom, also blanked and raised, was welded to the sides of the box in another jig, and the axle pads were welded in place at the same time; the pads fixed the gauge, and a tolerance of 0·05 inch in about 30 inches was maintained.

The drawbar which linked together mechanically laid mines and sinkers, and picked up the teeth of the conveying chain, was also made by jig-welding; in that case a tolerance of 0·010 inch was regularly maintained on a length of 54 inches, when the socket forging and the slot-key to the main bar were welded on.

In mooring rope connexions, after rope grips, splices, white-metal cones, etc., had been tried, swaged-on ferrules were used and produced the most reliable and best enduring connector. They were not dependant on the skill of the operator making the joint, and could be reproduced consistently. Means were evolved whereby any form of rope could be cut, and the ferrule could be fitted on the rope without its unlaying, so that the special preformed Trulay rope was not necessary. No swaged ferrule came off, and no rope broke at the ferrule.

A large hemp core and fine wires in the strands which formed a smooth rope tended to result in difficulties in swaging-on fittings. The core lent itself to rope yield, and the fine wires of the strands failed to embed themselves in the material of the ferrule; the keying of the rope to the ferrule might not be as strong therefore as in coarser wires.

Mine-mooring ropes were not of the very flexible type and had coarse wires with only a small hemp core, so that they made a very good swaged joint.

Captain R. OLIVER-BELLASIS, C.V.O., R.N. (London), speaking as Director of Underwater Weapons in the Admiralty, said that he believed the national defence could be properly secured only

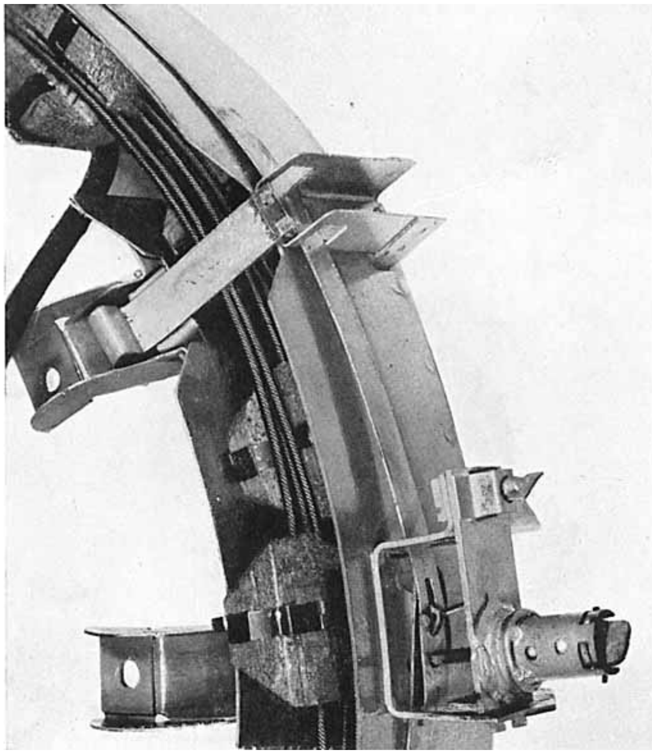
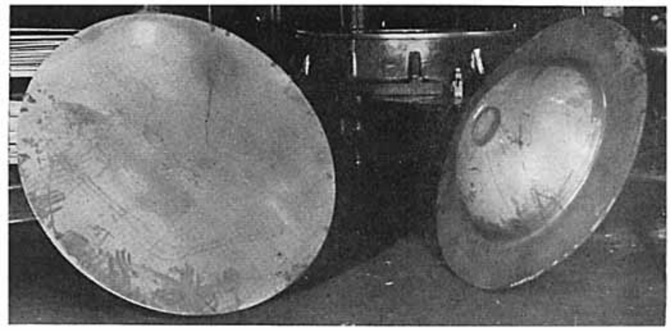
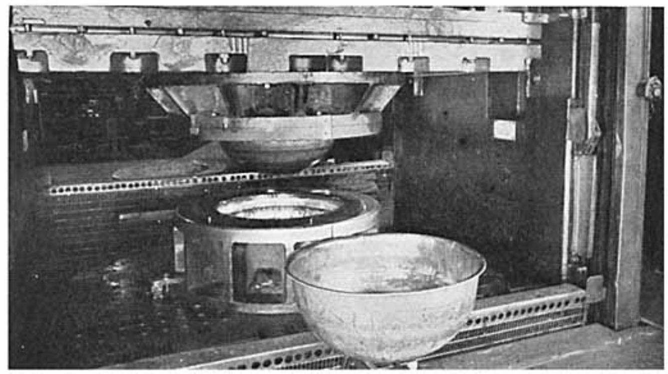


Fig. 69. Section of Container with Five-strand Mine Antennae in Place



a



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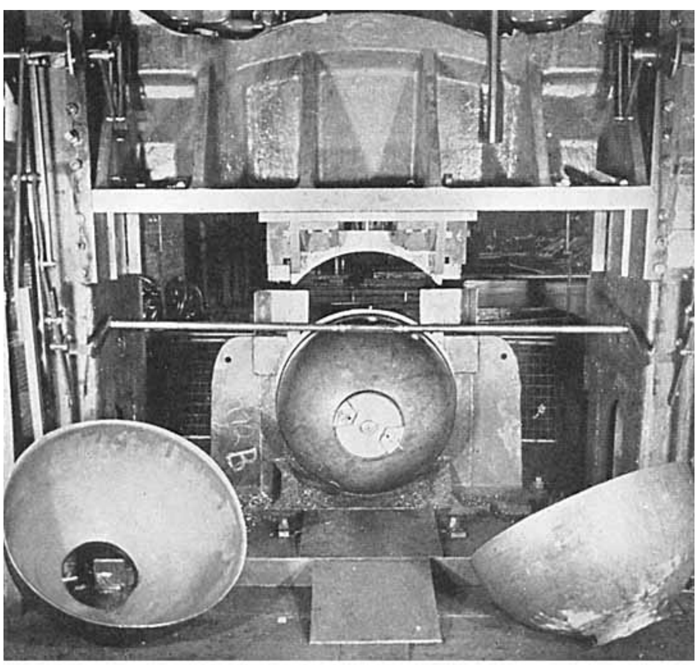

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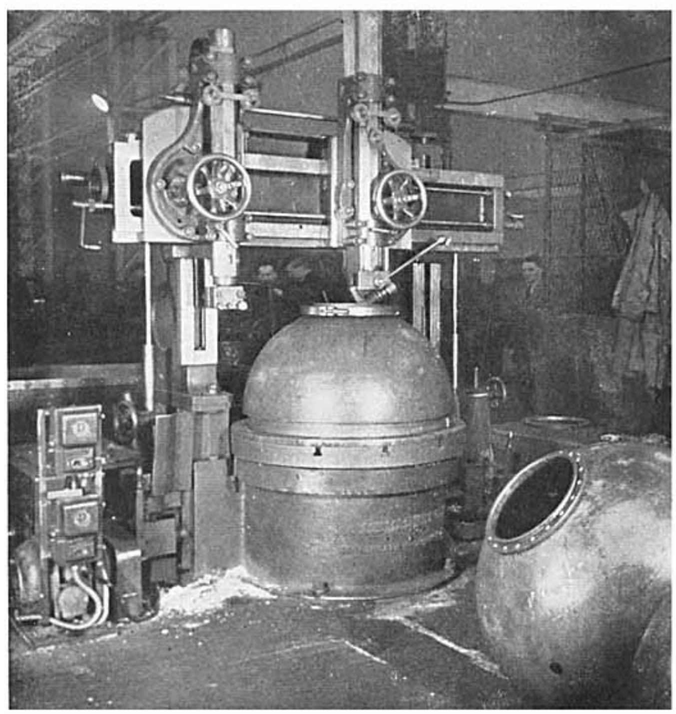
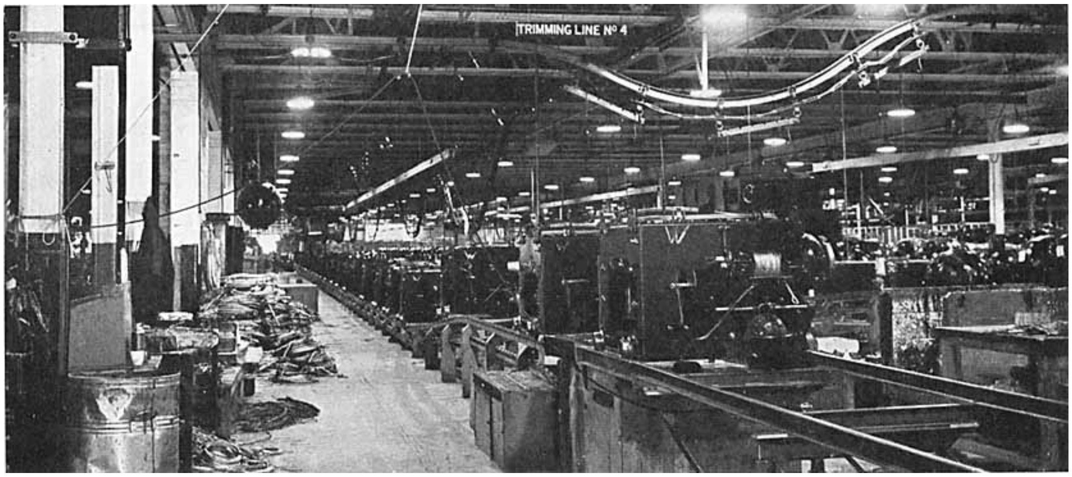


d

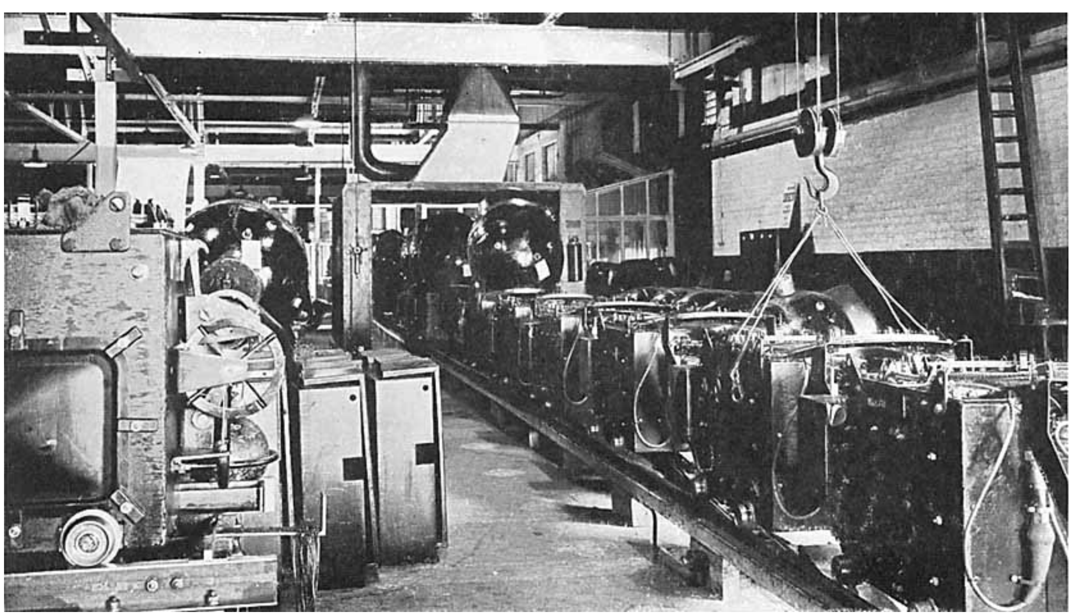
Fig. 71. The Manufacture of Mine Shells

a Blank before and after first forming operation.
b Finished hemisphere alongside press and die.
c Trimming surplus metal off the skirt.
d Spinning the mouth-piece flange.



a Sinker line.

b Mine assembly line.



c Married mines and sinkers being conveyed to railway trucks.

Fig. 72. The Manufacture of Contact Mines and Sinkers

by the full integration of industry and the Defence Services. His department was acutely aware of that.

The mine and the anti-submarine weapon had progressed far from the comparative simplicity of the 1914–18 war. There was, he thought, one error in Dr. Wadlow's historical review, in that magnetic mines called M. Sinkers were used in the 1914–18 war, off the Belgian coast. They were operated by a simple form of magnetic-dip needle; that was the type adopted by the Germans for their magnetic mine, which had an aluminium shell, and the inside of which was a first-class piece of instrument work. It must have represented a great effort on the part of their light, precision engineering industry. British mines were made with much greater regard for economy in industrial resources.

The clocks had to be accurate, of long life, and to work in unusual conditions. A clock from a German mine set to "sterilize" the mine in eight days had been recovered. The date selected was one of those forecast as the proposed date of the German invasion.

In any future war, it would be just as necessary as in the past to ensure the maintenance of sea communications. A glimpse of range and complexity of the problems which had to be faced today had been given. Success in a future war depended on the production of British research and development organization in peace; indeed the prevention of the outbreak of war might depend on one's being prepared for it. He asked the engineering profession and industry, therefore, for their sympathetic consideration when they were asked to find that rare man, the designer, or to take on research and development contracts, because they would remember the time when the German underwater offensive, first with mines and then with torpedoes, caused such heavy losses. That must not happen again, and he asked the members of the Institution to give their help in the future as they had done in the past.

Cdr. G. W. Harper, R.N. ret. (Rustington), said that it was very difficult to achieve a fully integrated organization, but the Royal Navy, the British manufacturers, and the men who had to use the weapons in action against the enemy had produced he thought, an extraordinarily able compromise, as one would expect.

Certain of the Allies were inclined to short-circuit the sometimes tedious processes of co-operation on safety arrangements, by sending a sample to sea and seeing whether it worked. That would not do, and he was sure that the British method was the best. During the war an Allied aircraft carrier was torpedoed in convoy in the Atlantic. It had its aircraft ranged on the flight deck ready-armed, not with the aircraft depth charge but with a type of bomb, which was not so good. When the ship listed 60 degrees before finally settling, all the aircraft lashings were carried away, and the aircraft fell into the sea. Owing to faulty design of safety arrangements, all the bombs went off under the aircraft carrier, thereby hastening its end. He emphasized again, therefore, the importance of integration between the user, the designer, the store-keeper, the manufacturer, and anyone else concerned.

Captain J. S. Cowie, C.B.E., R.N. (London), said that the minelaying campaign involved the laying of some 263,000 mines, of which some 80,000 were laid in enemy waters, and resulted in sinking or severely damaging 1,600 enemy ships. That meant about fifty mines to a casualty—costing about the same as two torpedoes.

The contribution made by basic research to results of the kind in question was widely appreciated, particularly by the public, but that of the engineer was not so widely known. That was particularly so in average Service circles. It was sometimes difficult to convince distinguished officers, who clamoured for something to be produced quickly, that the idea of the scientist could not be translated in terms of weapons and material until it had been engineered, and that that inevitably took time. It was equally difficult to convince the average user of warlike equipment that what seemed the slightest modification might cause the utmost dislocation.

He heartily agreed with what had been said about the importance of team-work. The success of our minelaying campaign was solely due to team-work, and the lack of German success was due to their lack of team-work.

Cdr. P. Bethell, R.N. (Glascoed), remarked that, whereas guns, ammunition, and other armaments were designed by the Armaments Design Department of the Ministry of Supply, underwater weapons were the responsibility of the Admiralty alone, no matter who used them. The Torpedo Experimental Establishment, which designed torpedoes, and the Admiralty Mining Establishment were directly responsible to the Admiralty, without any intervening boards or committees.

The Navy got quick results from those establishments directly responsible to the Admiralty. There might be a little tendency for the establishments to get into a groove and to develop obsessions and prejudices; they were not always, perhaps, fully in touch with other fields of armament development and research. But they had a body of highly specialized scientists and engineers whose working life was devoted to the perfection of one form of weapon and that method served the country well in the 1939–45 war. If Britain had not had in 1939 a design of depth charge which was safe, efficient, simple, and suitable for mass-production, the war would certainly have been lost by 1942. That depth charge was produced in astronomical quantities to a design, planned carefully well before the war, and almost the only modifications needed were the few, necessitated by tactical changes, described in Mr. Kirkby's paper.

The hoary and woolly maxim that the mine was the weapon of the weaker Naval Power had, in the past, led to stagnation; in the 1914–18 war, Britain did not have an efficient mine until an exact copy of the German one was made in 1917. More recently the race had been fairly even; sometimes one, and sometimes the other, was a little ahead. The German mine and depth-charge development was also done in Naval establishments directly responsible to the German Admiralty. In 1942, however, Goering brought about one of his cataclysmic changes by insisting that all aircraft-laid mines and depth charges, and all other weapons used by aircraft, must be the sole responsibility of the German Air Ministry. That, he himself believed, led to stagnation, but to a phenomenal increase in production, because the German Air Ministry had had very much better manufacturing priorities than had the German Navy.

To avoid the deck thrust of large mortars or depth-charge throwers, for light craft, the Germans used a rocket-propelled depth charge, giving no deck thrust at all: a depth charge very similar to our own was propelled by rocket for a range of about 650 yards.

Captain F. H. N. Vaughan, R.N. (Havant), said that they saw in Dr. Wadlow's the face that had sunk a thousand ships, in European waters.

In the Pacific war the same thing occurred, and the Americans, who did most of the minelaying, had used some British mines—which were always effective. A consignment of clocks was sent to the United States, and the Americans reported favourably upon them. The Japanese were brought to their knees by mines and submarines. The Germans used the submarine chiefly against Britain, and it was the humble depth charge which sank the majority. The secret of success was that combination which had been described—not always, but usually, a happy one.

Communications

Mr. A. Ogden (Weymouth) referred to a further method of minelaying from a submarine. Fig. 73 showed the port-side arrangements of a submarine fitted with two stern minelaying tubes from which mines carried within the pressure hull might be discharged.

In comparing the "loose bight" and "pilot wire" arrangements of mooring, the author stated that there was a tendency for pilot wire and mooring rope to become entangled during the ascent of the mine, when the latter system was used. In his own experience, however, that never occurred when a mooring rope was used, comprising six strands each of seven wires laid up in left-hand fashion, the strands being laid in right-hand fashion round one strand of seven wires laid up in right-hand fashion. Absence of rotation of the mine and consequent entanglement of pilot and mooring ropes during ascent would enable the pilot-wire system, which needed less sensitive pawling gear, to be more generally used.

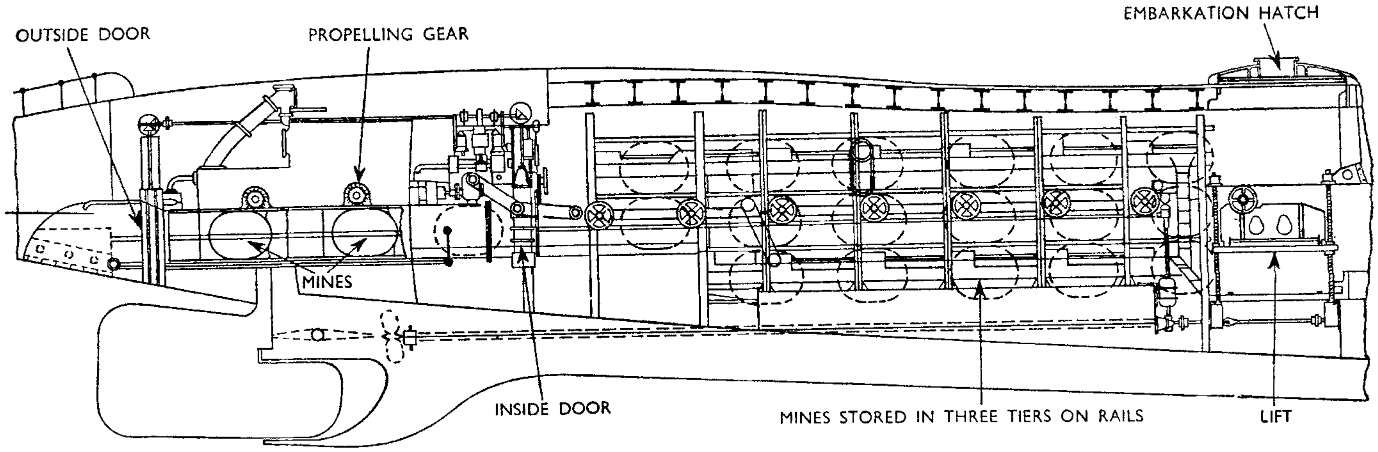


Fig. 73. Mining Compartment of a Submarine Fitted with "Dry" Internal Launching Tubes

Mr. E. W. B. Owen (Darlaston) wrote that his own firm, anticipating large-scale demand for mines in the event of war being declared, had themselves suggested that cold-press methods might be used, and had quoted a lower price for them. They received a development contract by which tools were made for half-scale mine shells by cold-press methods. The tools were satisfactory, and as a consequence Dr. Wadlow designed a 31-inch spherical mine to be made by similar methods.

The full hemisphere was drawn in one operation, and the hole was pierced in the same operation at the end of the stroke. The throat also was completed by press methods, while the stiffening ring—instead of being blanked, with a consequent waste of material—was produced by rolling and flash welding.

The cold press work on the 31-inch mine having proved successful, attention was turned to the 41-inch mine, but, owing to press limitations, they were unable to press the full depth. They produced the mines with end pressings each 4 inches shallower than the drawing dimension, but with a centre band 8 inches wider. The method of completion of the shells was similar to that used for the 31-inch mines.

Mr. R. F. Strickland-Constable (Oxford) and Mr. J. D. Francis (Southwick) wrote that the design of any weapon must always represent a compromise between the user requirements on the one hand, and certain physical limitations on the other.

Assuming, in the case of the Hedgehog described by Mr. Kirkby, that the weapon was to consist of a large number of contact charges, the user would like the following requirements to be met:—

(1) The explosive charge should be as large as possible.
(2) The range should be as long as possible.
(3) The sinking time in water should be as high as possible.
(4) The accuracy of projection should be as high as possible.

In meeting those requirements the designer had to take account of the following special physical limitations:—

(1) The projectile had to be man-handled on to the mounting.
(2) The thrust on the deck due to the explosion of the propellant charge must not exceed a certain limit without special precautions being taken.
(3) The length of the mounting was limited to about 6 feet.
(4) In all small vessels, weight above the centre of roll had to be severely restricted so as to preserve the stability of the vessel. Consequently the overall weight of any equipment to be placed on deck must be a minimum.
(5) The mounting had to be easily fitted into the considerable escort fleet already operating at the end of 1941. That limited the fitting time to that of the short refit periods undergone periodically by operating ships.

The conflict between user requirements and physical restrictions led to the compromises:—

(1) The projectile could not exceed about 60 lb. in weight, otherwise it could not have been loaded by hand on a rolling deck. With such an overall weight the maximum explosive which could be incorporated was found to be 34 lb. The diameter of the projectile was 6 inches: a lower diameter, giving greater sinking speed, would have been too long to handle conveniently, and would have held less explosive.

(2) The 6-inch projectile had a flattened nose which was necessary to give stability to its path underwater: it had a sinking speed of 24 ft. per sec. That could have been increased by streamlining the nose, but only at the expense of accuracy of underwater flight. It was gratifying that the Americans subsequently made a thorough study of that projectile in their well-equipped establishments, but finally adopted the design virtually unaltered not only for their version of the Hedgehog, but in a number of rocket-propelled adaptations used in other weapons.

(3) With a projectile of such a shape, it was possible to cram twenty-four projectiles into the mounting: that was achieved only by bringing the projectiles so close together that at one stage there was a danger of their touching when the full-roll-correction tilt was applied.

(4) The deck thrust on firing amounted to about 30 tons. An unreinforced deck could not stand such a thrust, and in destroyers it was decided to remove one of the forward guns, and to place the Hedgehog on the gun ring, where the thrust could be taken by the gun support. For that reason, as well as from general

considerations of deck space, the mounting was limited to about 6 feet in length. On Corvettes, additional deck stiffening had to be incorporated during a refit. The total weight of the mounting was about 2 tons, which was acceptable, and permitted easy fitting and handling.

(5) The range of the Hedgehog was actually fixed by a number of considerations, among which was the fact that errors of aim increase with range. It was also restricted by the increase in the weight of the tail tube of the projectile, required to withstand the shock of firing, when the range was lengthened. Increase in weight of the tail tube was, however, restricted by the requirement that the centre of gravity of the projectile had to be well forward to ensure stability in flight. The range was in the event fixed at 200 yards.

(6) Given a range of 200 yards, and given the accuracy of the weapon, the diameter of pattern needed to give an optimum chance of hit could be calculated on a basis of probability. The diameter was, in fact, fixed at first by a rather simpler consideration: the beam of a submarine was taken as 15 feet; if twenty-four projectiles are spaced at 13-foot intervals round the circumference of a circle, so that a submarine would just not be able to get in between two shots, a pattern 100 feet in diameter resulted. That was an unscientific procedure, and it was later realized that the optimum size was much larger. It was, however, too late to make a sufficient change, although the pattern diameter was slightly increased to about 120 feet.

Mr. Kirkby described the trunnion bearings as being of steel in bronze bushes. The connecting-rod bearing bushes were originally of bronze but were early changed to Tufnol, owing to the great difficulty of maintaining them free from corrosion: the change proved very satisfactory.

A gun barrel mounted on deck is apt to become full of water, so that a spigot projector had obvious advantages for naval applications. The possibility of firing away a gun barrel with every shot (virtually performed in the case of spigot projection) depended on the use of cold-drawn tubing—which could be supplied to very close tolerances. Even so the sealing of the cartridge presented special problems.

The battle of the Atlantic was won in 1943 by means of the depth charge. True, the Hedgehog was widely fitted throughout the escort fleet by the spring of that year, but, under war-time conditions, it took longer to train personnel to like and to use a new weapon, than it took to design and produce it. Consequently the successes of the Hedgehog came later in the war.

Dr. E. C. Wadlow and Mr. J. M. Kirkby wrote in reply to the discussion and communications that, prior to the war, the only method of manufacturing mine hemispheres that had been developed was the hot-pressing method described by Mr. Swan. To have produced all the hemispheres at the rate demanded by war-time requirements would have put an intolerable strain on the hot-pressing plant, and it was fortunate that presses proved to be available—both in capacity and in "daylight"—to produce the hemispheres "cold" as described by Mr. Longman. The requirement for the completed mineshells to withstand an external pressure of 375 lb. per sq. in. was due to the necessity that the shell must not collapse owing to the pressure wave in the water if the next mine in the field should be detonated.

Mr. Bossom has touched on a rather sore spot, from a designer's point of view, in his reference to forms of clock teeth. It was found, when it was desired to expand clock production, that each clock manufacturer in Great Britain had developed and used his own particular form of tooth, usually based on Continental practice, and had in stock only those cutters suitable for the range of tooth sizes used in his commercial products. Thus no uniformity existed, and firms were not easily able to produce teeth outside their normal range. The circular arc tooth, although not new, was suggested by the British Standards Institution as a means of obtaining uniformity between manufacturers. Its most important advantage in war time was that only a few cutters were needed to produce a complete range of tooth sizes, whereas with the epicycloidal tooth form, a separate cutter was required for each size.

The methods of galvanizing described by Mr. Watts undoubtedly enabled the very heavy demands for steel-wire rope to be met, but unfortunately the thickness of the zinc coating on each wire was inevitably reduced. That resulted in the rope's failing, owing to corrosion, considerably more quickly than was to be expected from trials carried out with ropes made before the war. The wire rope was the weak link in the endurance of a buoyant minefield, and the cost of renewing a minefield owing to its low endurance was out of all proportion to the cost of mooring rope. To produce mooring rope other than of the best possible quality was therefore highly uneconomic, though that had to be done in the circumstances.

Captain Oliver-Bellasis was correct in his reference to the error in the historical review in Dr. Wadlow's paper: the magnetic needle unit for use with a concrete ground mine was developed during the 1914–18 war and a small number of such mines were used operationally towards the end of that war.

The method of preventing the rotation of a mine when using the "pilot wire" method of pawling, as described by Mr. Ogden, was new to the authors; it would appear to overcome the chief objection to the arrangement.

Tufnol, as mentioned by Messrs. Strickland-Constable and Francis, was a more satisfactory material than bronze for the bearing for a steel shaft exposed to sea water, but it was preferable in such situations to avoid the use of steel if at all possible; after extensive experience, brass shafts in gun-metal bushes had been found the most satisfactory combination.

In conclusion, the authors thanked all those who, by taking part in the discussion, contributed some new view-point in the story of the mine and anti-submarine weapon from its conception and design, through manufacture, inspection, supply, and collaboration with the services, to its final discharge in action by the Royal Navy and the Royal Air Force.