Mechanical Engineering Aspects of Naval Mining

By E. C. Wadlow, B.Sc., Ph.D., M.I.Mech.E.*

The paper outlines some of the engineering problems which arise in connexion with naval mining, and describes some of the weapons and devices used by Britain and Germany in the war of 1939–45.

Although naval mining has a long history, its development is necessarily conducted under conditions of secrecy, and publication of information concerning it is possible only after a major war in which there has been a general disclosure of methods and materials employed by both sides.

The popular conception of a mine is a spherical buoyant object which will explode if hit by a ship. The buoyant contact type is, however, only one of many forms now available. A number of these are illustrated here, and the variety may surprise those not familiar with the subject. Methods of laying, general principles of operation, and safety requirements are described, and the mechanical details of design of mineshells, fittings, components for control and firing circuits, and other features are mentioned.

Naval mines have reached a state of considerable complexity and many fields of scientific knowledge are now called upon in making them effective weapons.

HISTORICAL

The use of drifting mines in naval warfare dates back to the sixteenth century, but Robert Bushnell, an American, is generally credited with the first development of the idea of attacking a ship with a submerged explosive charge. His mines were used by the Americans in the War of Independence (1776–7), though with little success.

Robert Fulton's buoyant mine, with a 100 lb. charge, was produced in 1810, and from this time, mines were employed with varying success in all the major wars. The introduction of the ground mine in 1855, the invention of the chemical horn by Herz in 1868, and the introduction of automatic depth taking for buoyant mines in 1886 are landmarks in the earlier technical development of mining equipment.

The war of 1914–18 was notable as being the first time that mining operations were conducted on a really large scale. The buoyant mines employed had either contact or antenna actuation systems (p. 29). Designs for acoustic and magnetic mines were prepared, but were never used in service.

Between 1920 and 1939 an improved range of buoyant mines was introduced into the British service. Satisfactory magnetic methods of firing applicable to both ground and buoyant mines were developed in this country and in Germany. The possibilities of laying from aircraft were also appreciated.

Intensive development of all types of mine immediately followed the outbreak of war—progress being most marked with aircraft laid mines and in firing systems for them. Although only magnetic, acoustic, and hydrodynamic pressure effects of ships, singly or in combination, have so far been employed in practice, it is probable that detailed consideration has now been given to most other possible systems of actuation.

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* Acting Principal Scientific Officer, Royal Naval Scientific Service.

TYPES OF MINE

Present-day naval mines fall almost entirely into two categories (*a*) ground mines which rest on the ground (i.e. sea-bed) after laying, and (*b*) mines which are buoyant and have to be moored in the desired position. A typical British ground mine (Fig. 1) is essentially a steel cylinder, the forward portion containing the explosive charge. At the rear end is a space for the components comprising the firing and control circuits. The parachute housing is attached to the rear of the component container.

This layout is not, of course, invariably adopted for all ground mines; various German designs carried a number of components in one or more pockets transversely to the major axis of the mine.

Buoyant mine units consist essentially of two parts—the mine, and the sinker. The former contains the explosive and the necessary volume of air to give the desired buoyancy. The latter is the unit which rests on the sea-bed and to which the mine is moored by flexible steel wire rope (Fig. 2, Plate 1).

The major fields of use of ground and buoyant mines, respectively, are determined largely by the relationship between weight of explosive charge and the distance at which the explosion will cause serious or lethal damage to the target.

For a given explosive and distance between charge and target, the damage is approximately proportional to the square root of the weight of charge. It depends additionally, however, on the position of fire relative to the ship, the strength of the ship itself,

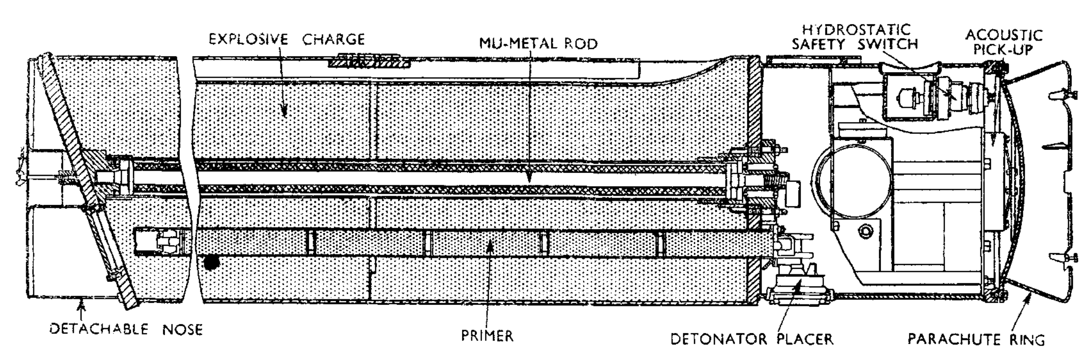


Fig. 1. Longitudinal Section of Ground Mine (British) Aircraft Laid

the nature of the sea-bed, the magnitude of the secondary, and possibly further pressure pulses generated by oscillations of the gaseous bubble resulting from the explosion, and other variables.

For these reasons, the ground mine is essentially a weapon for use in shallow water (e.g. a 750 lb. charge might give lethal damage in ten fathoms and worth-while damage in twenty fathoms if other factors, such as distance from base at which damage occurs, and weather conditions, influence the overall result). Buoyant mines, on the other hand, can be employed in certain circumstances (i.e. absence of tide) in depths as great as 1,000 fathoms.

METHODS OF LAYING MINES

Mines are laid from either aircraft, surface vessels, or submarines. The speed and range of the aeroplane has so far made it the means best adapted for offensive mining, and as the majority of offensive mining of the 1939–45 war was conducted in the shallow waters fringing the North European mainland, where ground mines were eminently suitable, these have inevitably come to be associated with aircraft minelaying.

At the same time, many of our defensive minefields were required in water too deep for the employment of ground mines, and fields of buoyant mines were necessary. If reasonably distant from the enemy's coast, such minefields can be laid most effectively by surface vessels. Large numbers of mines can be laid in one operation with greater accuracy of positioning.

Submarine laid mines may be used when it is desired to mine relatively deep water close to the enemy's coast without disclosing the presence of the minefield. Ground mines laid from submarines have a more limited application than buoyant mines for the depth of water must be great enough to allow the submarine to manoeuvre, and at the same time must generally not be too deep for the mine to be ineffective against surface targets.

Laying from Aircraft. It is a British requirement that mines shall be capable of being carried in the bomb racks of bomber aircraft, and thus the shapes and sizes of mines have to a large extent been controlled by aircraft bomb stowage considerations (Fig. 1 and Fig. 3, Plate 1).

It is generally necessary to restrict the terminal velocity by using parachutes, for the mine and its delicate components must survive impact with the water and be capable of operating months after laying. The early German mines with delicate gimbal-mounted magnetic firing units (Fig. 24, Plate 2) had parachutes twenty-four feet in diameter reducing their terminal

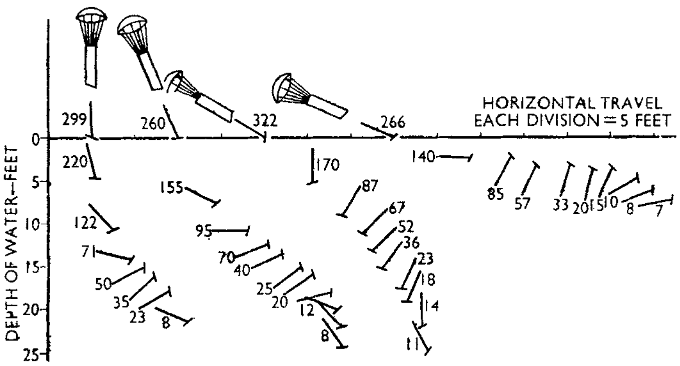


Fig. 5. Typical Underwater Trajectories of an Aircraft Laid Ground Mine

Numbers indicate velocity in feet per second at each position along trajectory.

velocity to about 75 ft. per sec. British practice has been to employ smaller parachutes to limit the terminal velocity to between 200 and 250 ft. per sec. Certain versions of a German mine (Fig. 4, Plate 1), with circuits requiring only very robust components, and used without a parachute, had a terminal velocity of about 1,000 ft. per sec.

On entering the water, the mine suffers an impulsive velocity change, for the effective mass is suddenly augmented by a certain mass of water which is carried along with the mine. If the underwater trajectory is a continuation of the air trajectory, the reduction in velocity due to frictional drag will be small, and the mine will hit the bottom in shallow water at a high speed. This may damage the shell and the components, or the mine may bury itself deeply in the sea-bed, which may delay or prevent the operation of its arming devices.

An effective method of preventing the mine from following its air trajectory underwater is to chamfer the nose to an angle of about 20 deg. (Fig. 1). A dummy fairing necessary to give good air ballistics is knocked off on impact with the water and the mine is turned off its air trajectory by out-of-balance forces on the nose (Fig. 5). The forces to be sustained during impact and turn-off are considerable. With high release speeds and low heights of release ricochet may occur on hitting the water. The behaviour of the mine in all these respects can generally be predicted with considerable accuracy from model experiments.

Laying from Surface Vessels. Surface minelayers range from fast motor torpedo boats carrying half a dozen mines or so, up to specially built vessels or converted merchantmen carrying several hundred mines.

Each mining deck of a large minelayer has two or four pairs of channel-section rails with a system of points as necessary, running the length of the ship to port and starboard apertures in the stern of the hull.

The mine units are lowered through hatches on to the rails which have detachable upper flanges at the loading points.

Mines are either laid manually or by mechanical means. With manual laying the rails are fitted with hand-controlled stops which form a laying "trap" and prevent more than one mine unit at a time from being laid (Fig. 6). The normal spacing of buoyant mines after laying is about 150 feet and in order to give

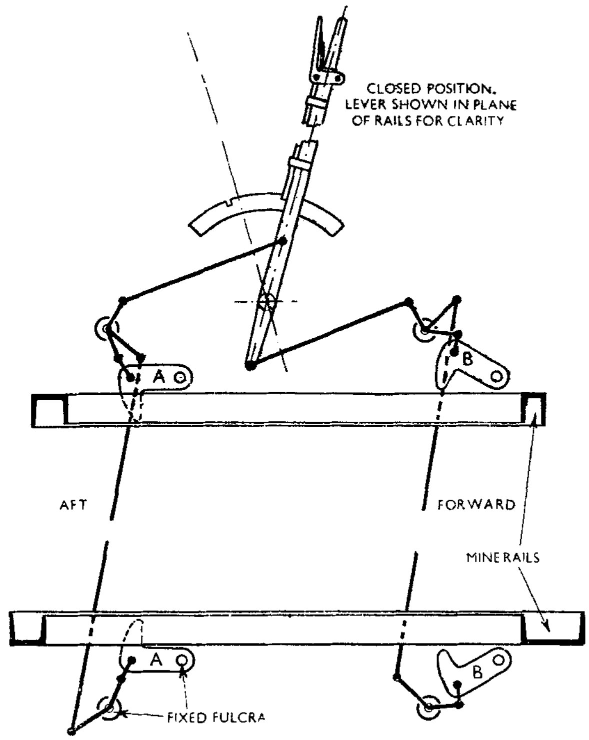
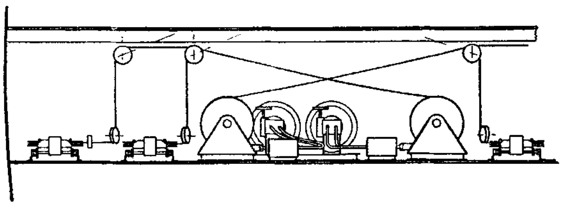


Fig. 6. Minelaying Trap for Surface Minelayer

more time for handling, it is usual to lay alternately from port and starboard "traps".

The method of bringing mines aft for both mechanical and hand laying is briefly as follows (Fig. 7). A wire rope, anchored at a buffer fitted with a hydraulic overload release, is taken forward along the ship's deck, and passed round horizontal pulleys mounted on a "hauling aft bogie". It is then taken aft again and led on to a large diameter drum capable of being driven at variable speed. The bogie can be inserted into, and removed from, the train of mines at points where the upper rail flange is detachable. The mines can thus be hauled aft in groups to maintain a steady supply at the laying traps.

With hand laying, the sinkers are fitted with simple buffers only, to prevent mechanical damage. Vessels fitted for hand



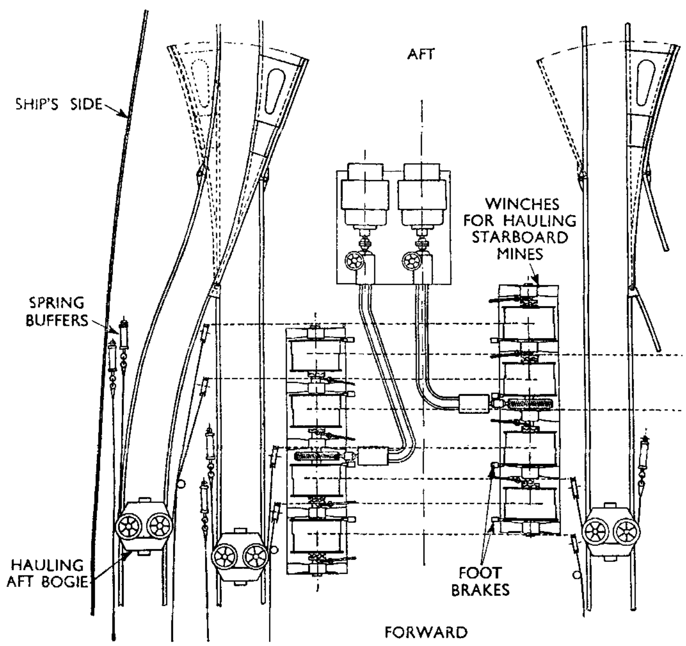


Fig. 7. Hauling Aft Arrangements for Large Minelayer

laying, and carrying more than 100 mines, are fitted with a McCaffery Klyne clock to indicate automatically at the traps the moment for laying.

Mechanically laid units must be coupled together on the rails and spaced accurately. Electrically or hydraulically driven laying gear consists of a special chain carrying four teeth passing round

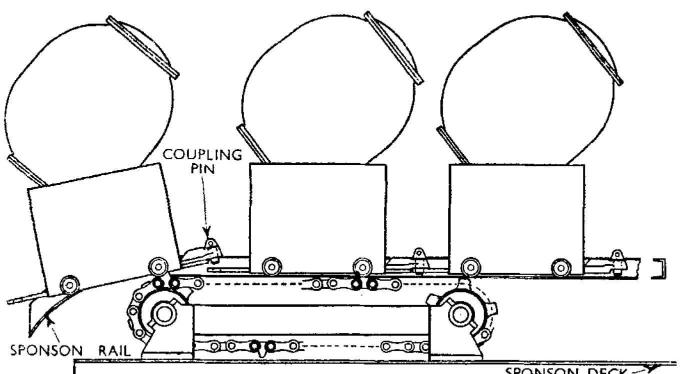


Fig. 8. Minelaying Equipment for Surface Minelayer

sprocket wheels spaced at about 6 ft. 6 in. centres, and placed between, and just below, the mine rails (Fig. 8). As the units are pulled aft and the end one passes over the sponson, the forward end of its drawbar (i.e. that pointing towards the bow of the ship), together with the drawbar pin, is lifted clear of the aft end of the drawbar of the following unit. For separation to be accomplished satisfactorily, the drive must be taken up by the second unit from the end for a short time before the end unit is released. This is accomplished by having the chain tooth pitch 0·1 inch shorter than the drawbar slot pitch.

Most mines will withstand being laid at speeds up to 20 to 24 knots but, of course, many minelayers are themselves not capable of such high speeds.

Laying from Submarines. With submarine laying, where the accurate location of the site for laying may be a matter of some difficulty, the taut wire measuring gear (Fig. 9) which pays out fine piano wire as the vessel proceeds, and measures the length paid out, is invaluable.

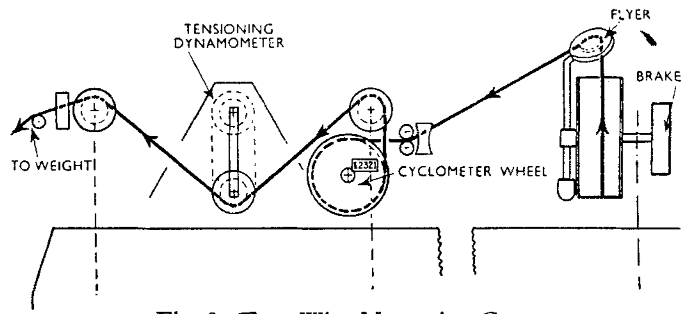


Fig. 9. Taut Wire Measuring Gear

A drum, carrying 140 miles of wire, is held stationary and the wire is taken off by means of a flyer arm rotating about an axis coincident with that of the drum. The counting gear registers to 1/1,000 of a mile. The wire is taken through a gland in the hull of the submarine to a special grapnel, which is released about two miles before it is desired to begin measurement.

Three methods of laying are commonly employed:—

(*a*) Laying from tubes. The mine is ejected from a torpedo tube in exactly the same way as a torpedo. Mines may be either ground or buoyant (Fig. 10).

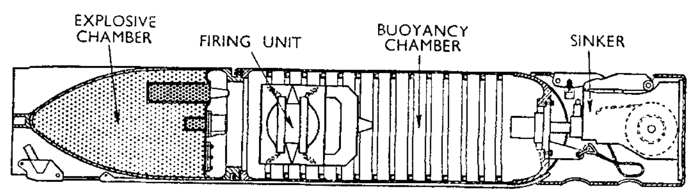


Fig. 10. Buoyant Mine-Sinker Combination, Submarine Laid (German)

(*b*) Laying from rails on the deck—the method being very similar to that described on p. 23.

(*c*) Laying from vertical wells or tubes. These may run through the pressure hull, or may be placed in the saddle tanks (Fig. 11).

For method (*a*) the mine must be fitted with stops and handling arrangements exactly as for a torpedo. In British practice, however, for economy of production, it is not usual to machine the mine body all over, but to roll the mineshell to a diameter slightly smaller than that of a torpedo, and to make up to the full diameter, where necessary, by welding on "rubbing strips". When laying mines, a certain leakage of air past the mine can be accepted.

Method (*b*) differs from that employed with surface minelayers only so far as all the controls are inside the submarine and special indicators are necessary. Up to fifty units may be carried.

With method (*c*) the mine units are fitted with vertical guide bars carrying wheels which engage in vertical rails in the tubes or wells (Fig. 11). Each well may contain one or more units, which are held in position by catches, and fall out under gravity when the catches are withdrawn. It is unusual to be able to gain access to the mines after they have been embarked.

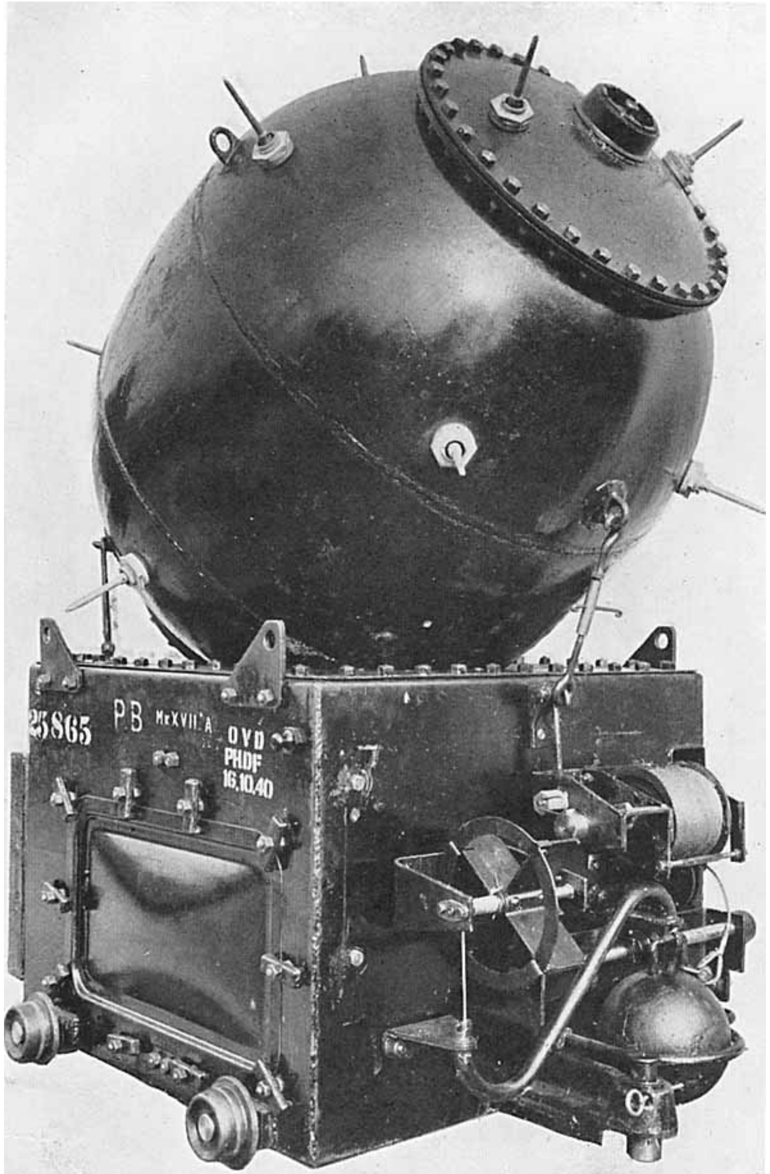


Fig. 2. Buoyant Mine-Sinker Combination (British) Shiplaid

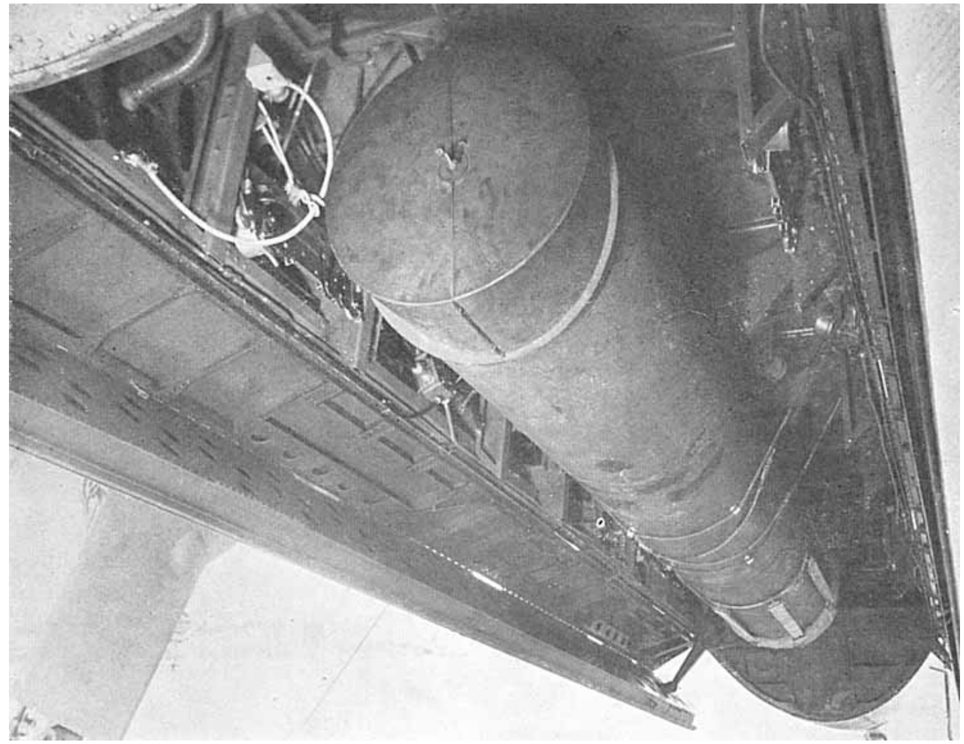


Fig. 3. Ground Mine (British) on Avenger Aircraft (Internal Stowage)

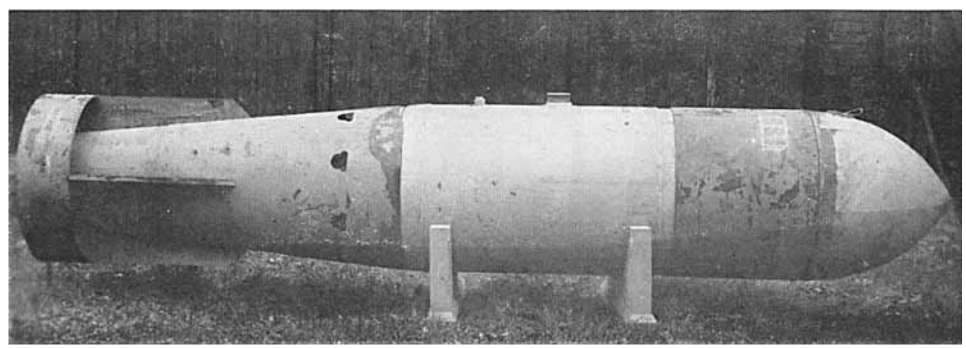


Fig. 4. Parachuteless Mine (German) before Laying

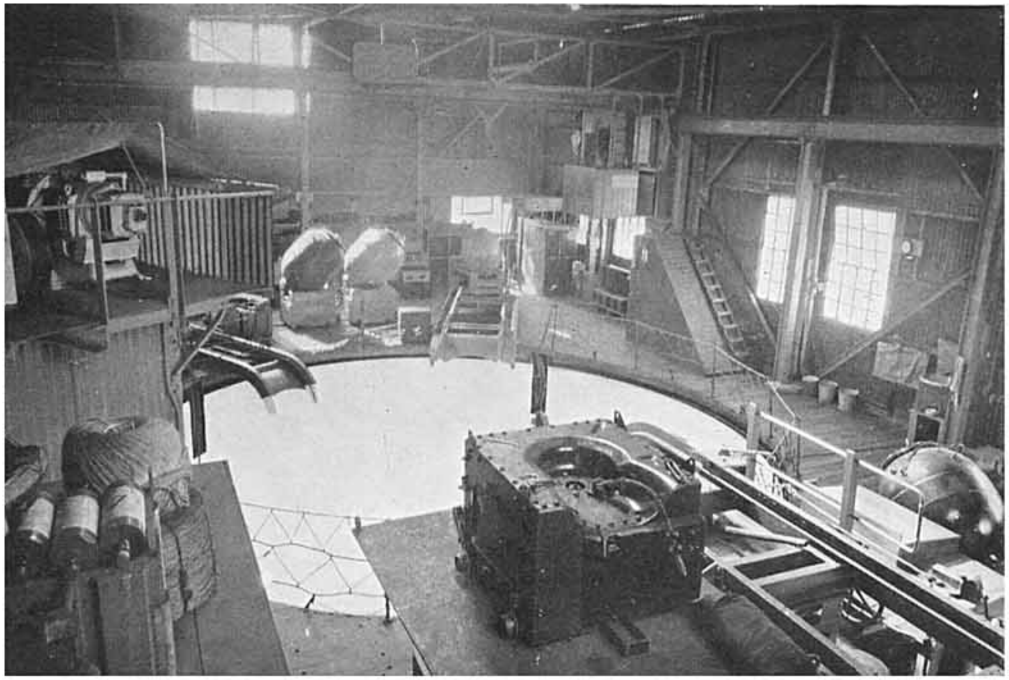


Fig. 14. Mining Tank Showing Arrangement of Working Deck

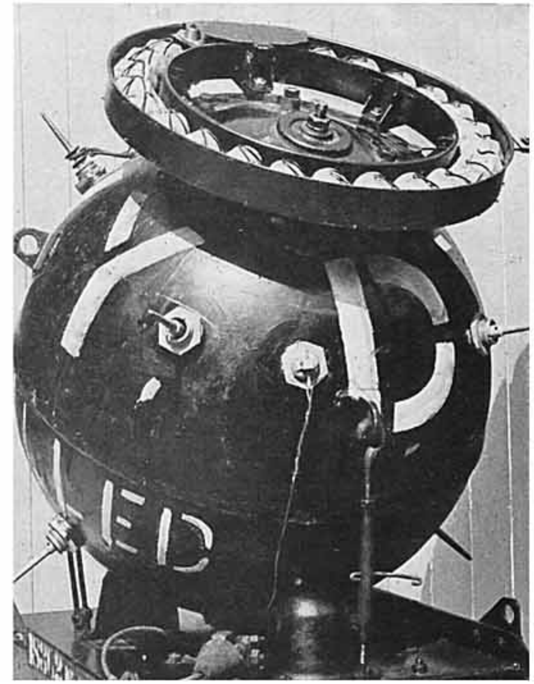
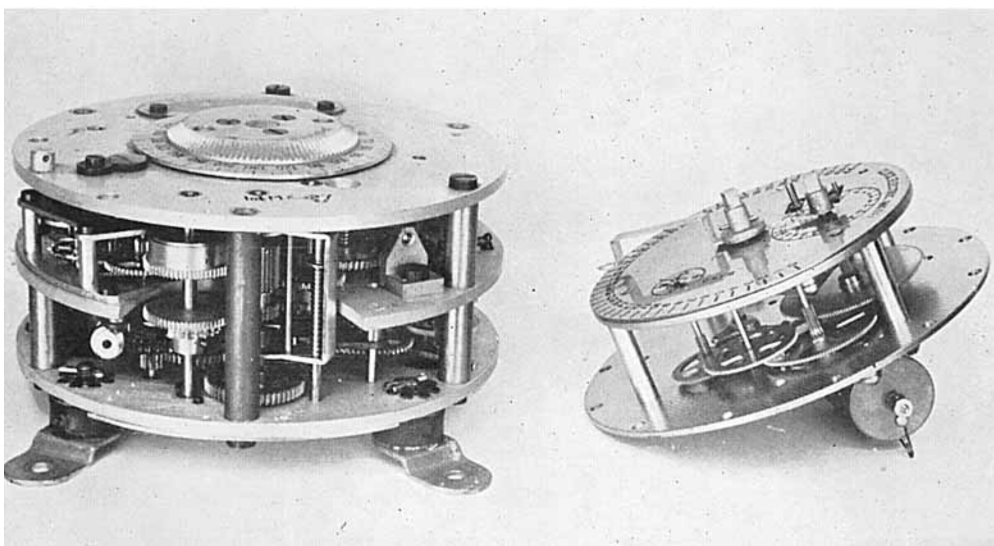


Fig. 18. Stowage of Cod Line on Buoyant Mine (British)



a Fig. 20. Clocks for Sterilizers *b*

(*a*) German. (*b*) British

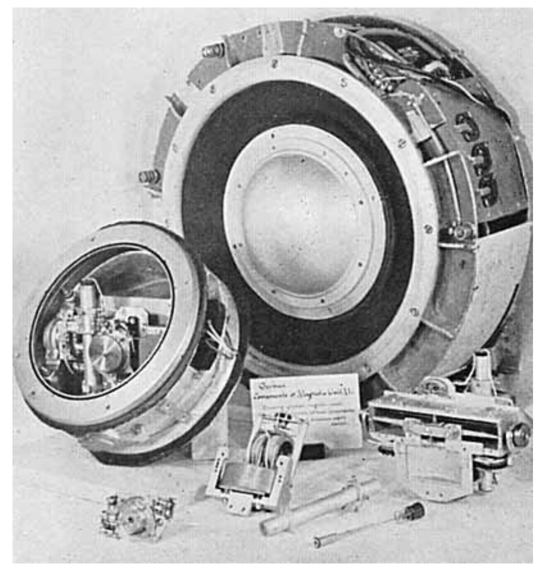


Fig. 24. Magnetic Needle Firing Unit (German)

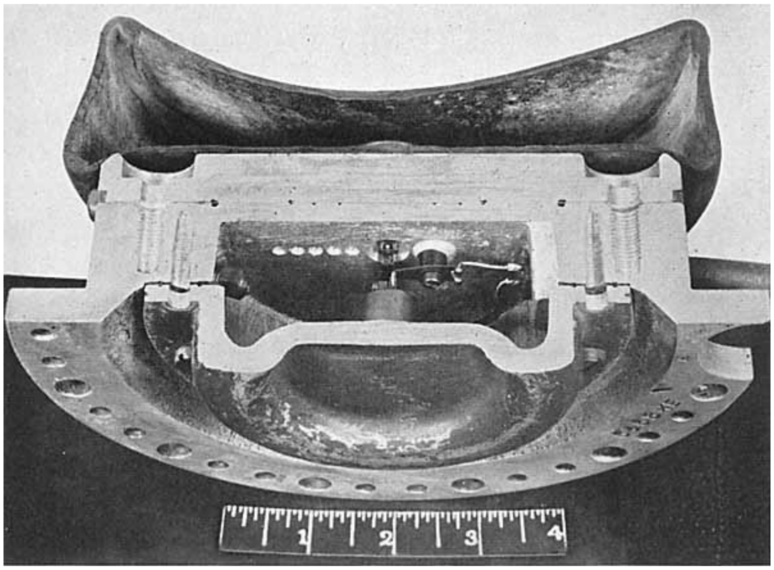


Fig. 25. Pressure Firing Unit (German)

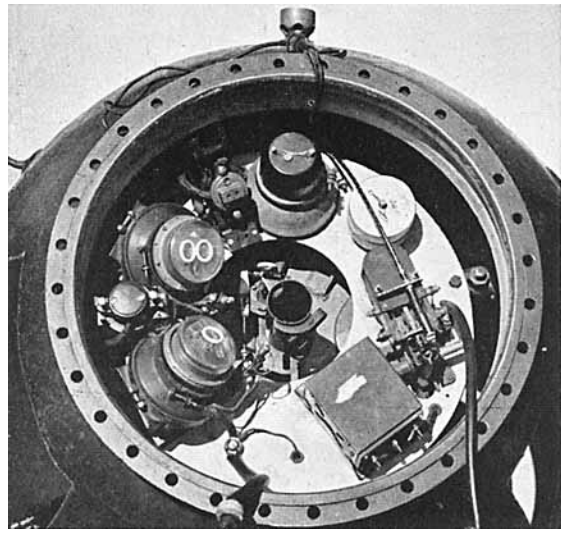


Fig. 28. Mounting of Components in Buoyant Mine (British)

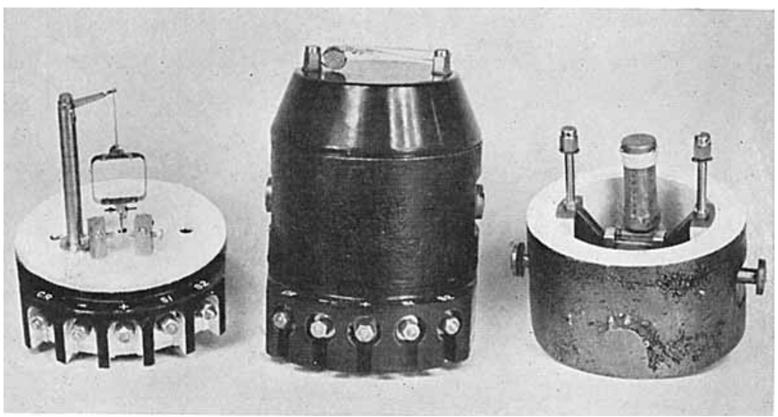


Fig. 31. Relay, complete and dismantled (British)

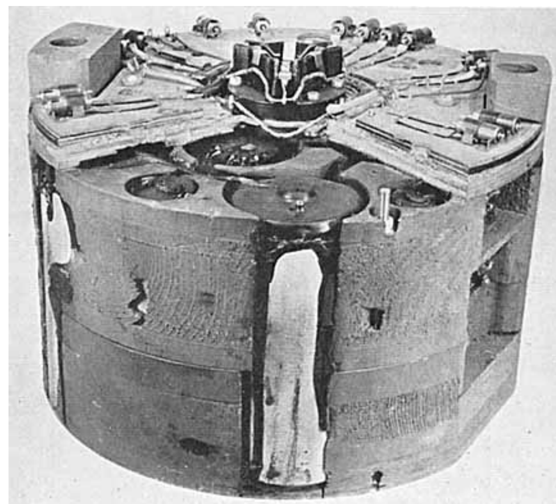


Fig. 29. Mounting of Components in Parachuteless Mine (German)

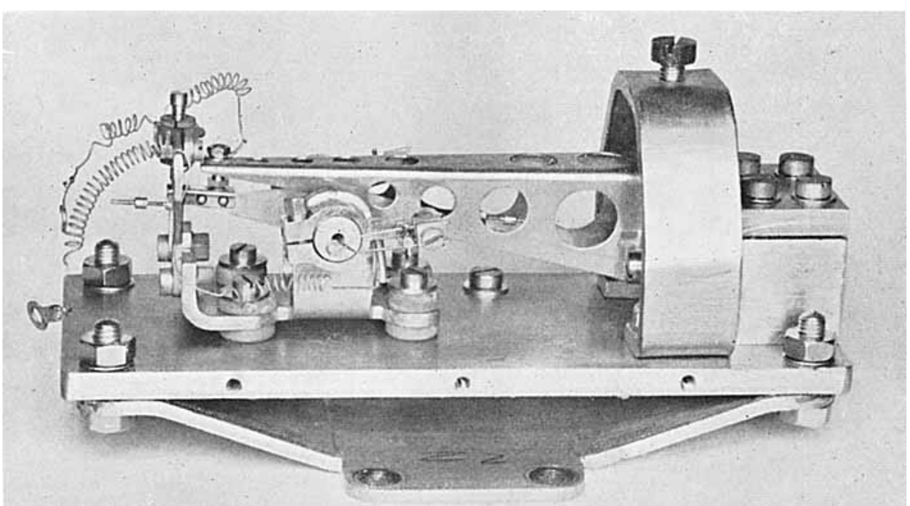


Fig. 32. Acoustic Pick-up (British)

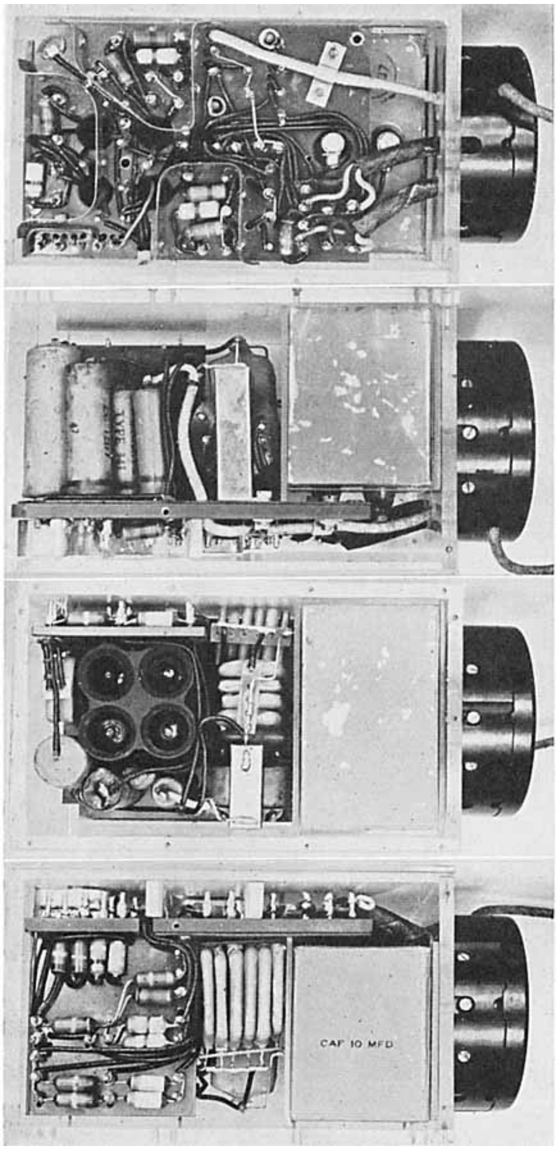


Fig. 33. Amplifier, before Waxing (British)

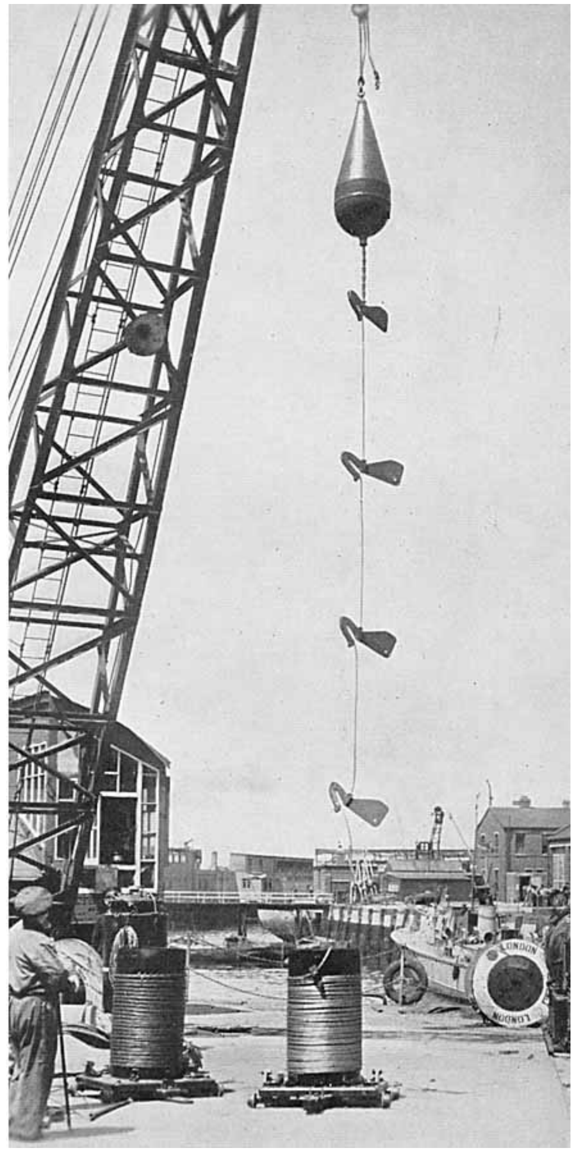
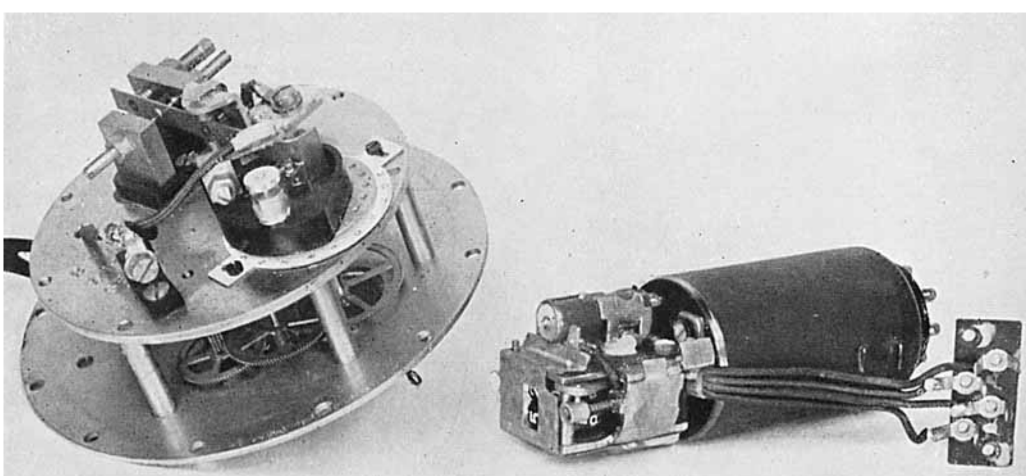


Fig. 35. Obstructor, with Static Cutters (British)



a Fig. 36. Ship Counters *b*
(*a*) British. (*b*) German

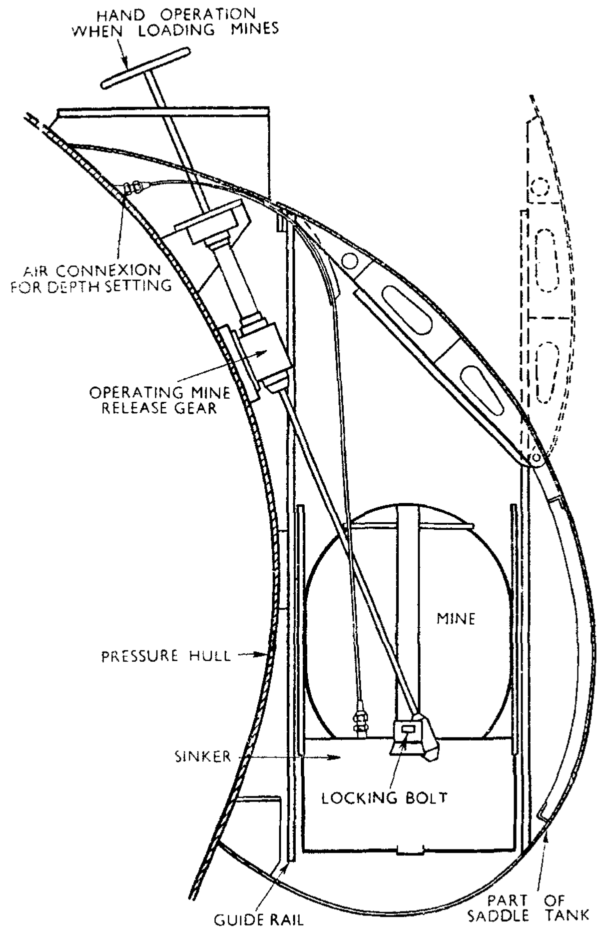


Fig. 11. Minelaying Well in Submarine

DEPTH-TAKING ARRANGEMENTS

Depth-taking Arrangements with Surface Laid Mines. Mine-sinker units laid from surface minelayers generally employ "plummet" depth taking.

With this system, a catch which locks the depth-taking and mine-release mechanisms and prevents premature operation is freed when the unit leaves the minelayer rails (Fig. 12*a*).

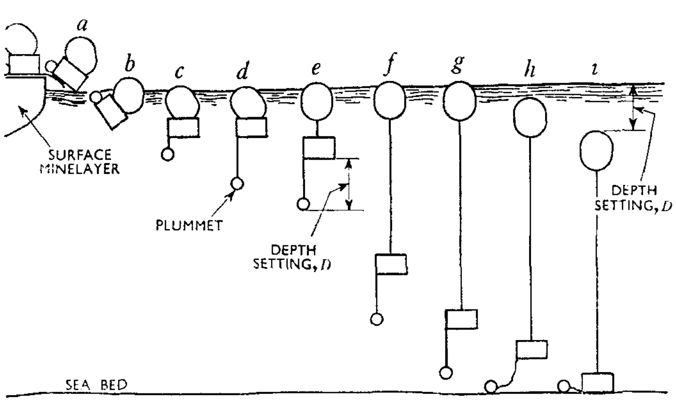
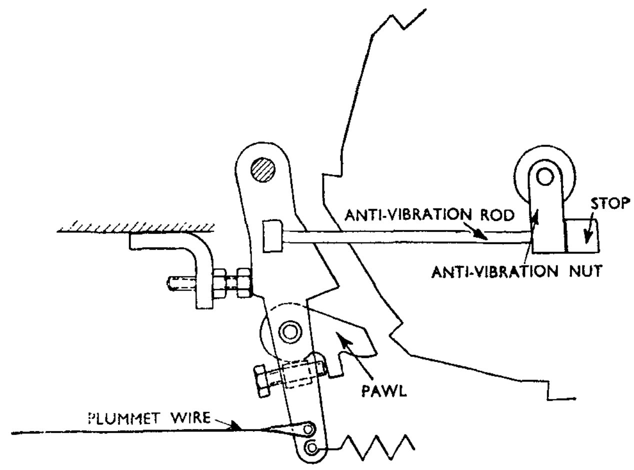
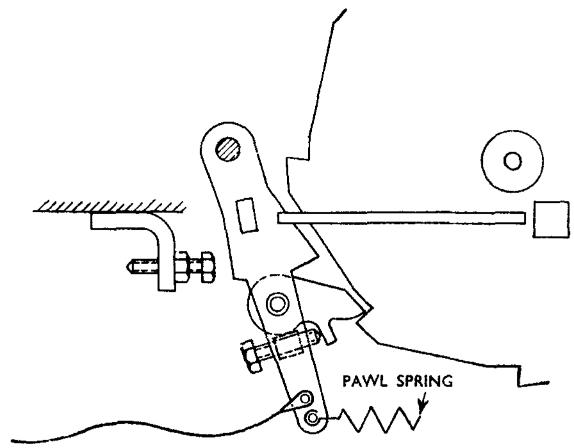


Fig. 12. Sequence of Events with Plummet Depth Taking

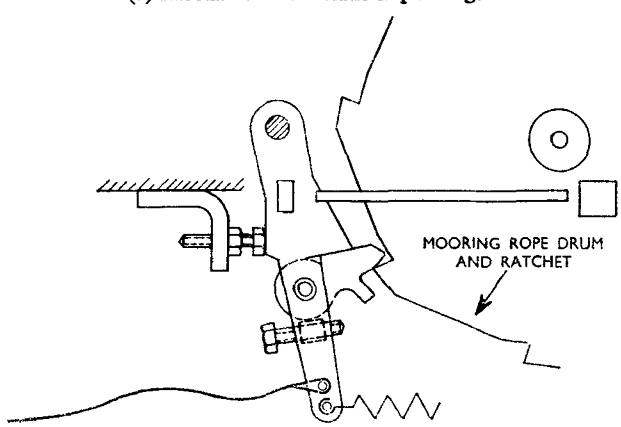
While the combination is still floating on the surface of the sea (the sinker being intentionally made almost watertight), the heavy iron plummet falls clear of the sinker (Fig. 12*c*), and as it descends (initially under the control of a paddle or other type of delay device so as to defer release of the mine until the unit has become more stable in the water) it pulls off wire from the depth setting drum. When the desired amount has been pulled off (Fig. 12*d*) the sudden tautening of the plummet wire is utilized to release the mine from the sinker. This operation removes a flooding bung from the sinker which commences to flood and sink, leaving only the mine on the surface. The mooring rope is pulled off the drum inside the sinker as the latter descends—a friction mechanism, paddle brake or similar device, being employed to prevent overrunning of the drum. The drum is also provided with a heavy ratchet wheel, integral with one of the drum cheeks. Opposite the ratchet is a pawl, carried on a pawl lever (Fig. 13). A strong spring tends to pull the pawl into engagement with the ratchet, but a wire attached to the plummet applies a force in the opposite direction sufficient to keep the pawl from engaging the ratchet as long as the plummet hangs freely from the sinker (Fig. 12*c* to *g*).



(*a*) Mechanism with anti-vibration rod engaged, and tension in plummet wire.



(*b*) Mechanism at instant of pawling.



(*c*) Mechanism with pawl fully locked.

Fig. 13. Sinker Pawling Mechanism with Plummet Depth Taking

When the plummet reaches the sea-bed (Fig. 12*h*) the pawl spring takes control, and pulls the pawl into engagement with the ratchet, thus locking the mooring drum. No further mooring rope is then run off, and—as by now the sinker is full of water and is much heavier than the mine is buoyant—the mine is pulled down until the sinker reaches the sea-bed (Fig. 12*i*). Ignoring minor corrections which have to be applied in practice, the distance which the mine is pulled down (or the depth setting) is essentially equal to the distance the plummet was hanging below the sinker.

When the mine is released and the sinker begins to descend, its motion may be jerky, and the variable tension in the plummet wire cannot be relied upon to overcome the pawl spring. It is, therefore, usual to arrange that the pawl is held out positively until the mooring drum and its spindle have made two or three revolutions. A nut, restrained from rotating, is mounted on a threaded extension of the mooring drum spindle, and interferes with the pawl lever, thus preventing its movement until disengaged by rotation of the spindle.

Once the sinker has pawled, the mooring drum must never become unlocked. With a simple pawl and pawl lever, this might happen if for any reason a strong pull was again given on the plummet wire. The mechanism is therefore arranged to give a toggle action on pawling (Fig. 13). This arrangement, known as an Anthony pawl after its originator, was first introduced in 1916.

The conditions under which a sinker has to work are often severe. When laying in adverse conditions the height of drop from the sponsons to the water may be up to 30 feet. The unit then enters the water upside down and may be oscillating violently while the plummet is running off. Very careful attention has therefore to be given to the run of the lanyards to avoid fouling, and post-mortem examination of failures occurring at sea is rarely possible. A mining tank 60 feet deep and 30 feet diameter, fitted with a platform which can be raised and lowered the full depth of the tank, has therefore proved invaluable in development work on buoyant mine-sinker units (Fig. 14, Plate 2).

In deep water, unlaying and stretch of the mooring rope may be important. The correction may be as much as 20 feet for 1,000 fathoms of $\frac{3}{4}$-inch circumference rope with a 840-lb. buoyancy mine.

Depth-taking Arrangements with Submarine Laid Units. The primary desiderata with submarine laying are (*a*) the mine must never show on the surface, otherwise it might compromise the submarine, and (*b*) the mine must not take up its depth until the submarine is a safe distance away.

In order to meet requirement (*a*) it is usual to employ hydrostat depth taking, using either the loose bight or the pilot wire system, respectively.

While aboard the submarine, a tube or rail held safety device prevents separation of mine and sinker. On laying, the complete

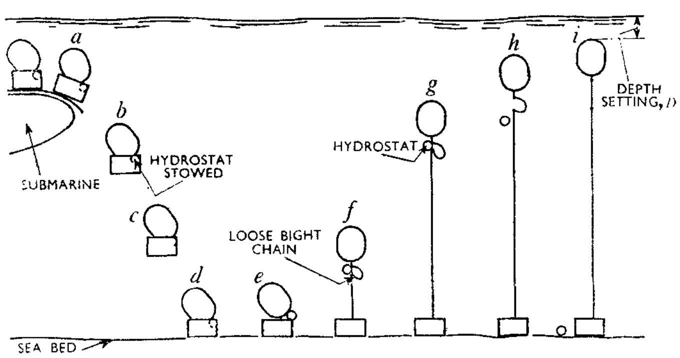
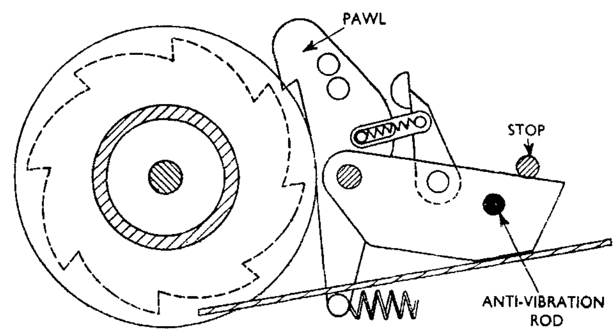


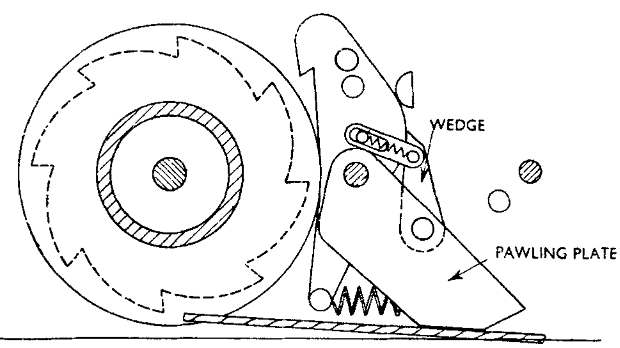
Fig. 15. Sequence of Events with Hydrostat Controlled Loose Bight Depth Taking

unit falls to the sea-bed (Fig. 15). The positive mine buoyancy is utilized to separate the mine from the sinker, but the operation is delayed for some minutes by a dashpot or other delay device. When separation is effected (Fig. 15*e*) the mine rises and pulls off rope from the mooring drum inside the sinker.

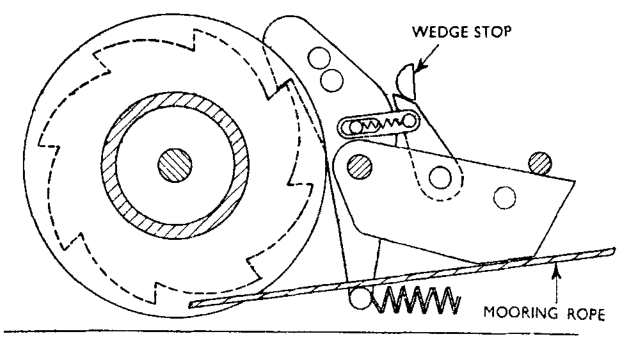
Typical pawling arrangements inside a sinker are shown in Fig. 16. The mooring rope, after leaving the drum, passes under a spring-loaded pawling plate to which the pawl is attached. The pawling plate is held up by an anti-vibration gear until the mooring drum has made several revolutions, by which time the tension in the mooring rope is steady and can be relied upon to hold the pawling plate up against the tension of the pawling plate spring which tends to pull it down. During this period, the wedge is on the side of the wedge stop remote from the ratchet.



(*a*) Tension in mooring rope. Anti-vibration gear still engaged.



(*b*) Loose bight released, slackening mooring rope. Pawling plate drops.



(*c*) Tension in mooring rope renewed. Drum locked by pawl.

Fig. 16. Sinker Pawling Mechanism with Loose Bight Depth Taking

The hydrostat rising with the mine functions at a predetermined depth, releasing a bight of chain which, from this instant, forms part of the mooring. The sudden release of this additiona length of mooring momentarily slackens the tension in rope, allowing the pawling plate to drop, and the wedge to fall clear of its stop. A fraction of a second later, however, the full tension in the mooring rope is restored and the pawling plate is jerked upwards. But the wedge, under the control of a spring, is now on the other side of the wedge stop, and, therefore, forces the pawl into engagement with the ratchet, thus locking the drum. A spring-loaded plunger prevents the pawl disengaging.

With the pilot-wire system, the hydrostat on the mine carries a drum of fine wire, the free end of which is attached to the pawl lever inside the sinker, the pawl being held out of engagement with the ratchet by a spring. As the mine rises, wire is paid off the hydrostat drum until the hydrostat operates, locking the hydrostat drum. The pilot wire is thus suddenly tautened, engaging the pawl with the ratchet and locking the drum.

Mines with hydrostat depth taking should be laid at slack water. If laid in a tide, the mine will rise diagonally, and as the hydrostat will operate at the correct depth, the length of rope pulled off the drum will be greater than the true vertical distance. It should perhaps be mentioned that all depth settings are always measured from low water datum.

The loose-bight system is generally preferable to the pilot-wire system. With the latter there is a possibility of rotation of the mine, during its ascent, causing the pilot wire and the mooring rope to become entangled. An objection to the loose-bight system is that mud inside the sinker may slow down the action of the pawling plate, and allow the mine to surface before pawling takes place.

CONDITIONS OF SERVICE

Conditions of Service when Laid. The only natural effects likely to interfere with the performance of a ground mine after laying are (*a*) movement on the sea-bed due to scouring action of tides, which may produce premature firing of certain types, and (*b*) subsidence into mud, which may delay the operation of arming devices, interfere with the response of the mineshell to acoustic vibrations transmitted through the water, and prevent other types, requiring the access of water, from actuating. Buoyant mines, when moored, may be subjected to (*a*) action of tidal streams and (*b*) subsurface action of waves.

Tidal streams have two effects. The first is to swing the mine and its mooring rope away from the vertical, causing "dip" (Fig. 17). The second is to produce forced oscillations of the mine and rope in a plane roughly at right-angles to the direction of the tidal stream.

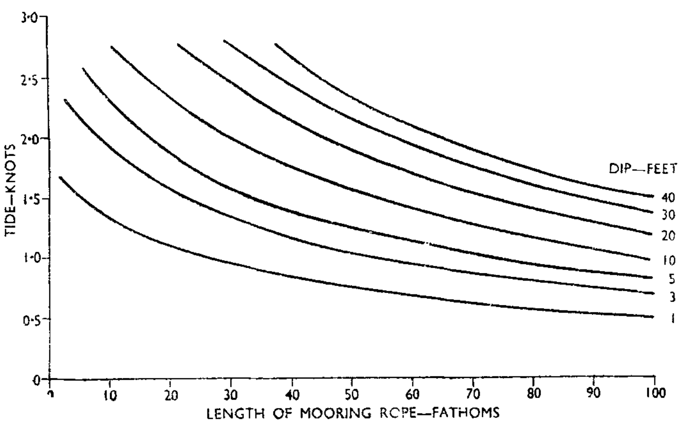


Fig. 17. Variation of Dip with Tide for Typical Mine

Mine buoyancy, 620 lb.; mine diameter, 41 inches; mooring rope circumference, $1\frac{5}{16}$ inches.

During the 1914–18 war, attempts were made to produce mines which would maintain a constant depth setting, regardless of the tide. The difficulty is that the forces required to operate the mechanism are large, while those available are small. Work on these lines has long been abandoned, and the modern solution to the problem is to employ mines with non-contact firing systems or else to extend the range of the contact type by flexible and buoyant extensions.

In one arrangement, as shown in Fig. 18, Plate 2, a piece of cod line, 70 feet long with corks at intervals of a few feet to give buoyancy, is attached to one of the switch horns of the mine, which is actuated if the line becomes entangled in a ship's propeller.

An alternative scheme, used with antennae mines (p. 29), employs a floating upper antenna, consisting of 60 feet of five-start hollow strand of copper or bronze wires, fitted with corks and scraping points at intervals. This particular type of strand, specially developed for the purpose, has marked self-straightening properties, as opposed to the behaviour of a normal strand which invariably tangles itself up when released.

Lateral oscillation of buoyant mines caused by tidal streams may cause premature explosions with certain systems of magnetic firing. The subsurface action of waves causes similar oscillations in the plane of the direction of their propagation. While the oscillations due to tidal streams can be reduced by fitting fins to the mine, no way of avoiding the second mode of oscillation due to waves has yet been devised.

The subsurface action of waves is greater than is frequently appreciated. The orbits and velocities of particles of water in waves are diminished approximately by one-half for each additional depth below the mid-height of the surface waves equal to one-ninth of the wave-length.

Therefore a buoyant mine relatively near the surface has considerable lateral movement in heavy seas, and its moorings are subjected to many cycles of stress. Premature breaking adrift may result and units which have an endurance of two years in relatively sheltered waters may last only a few months, or even weeks, when exposed to conditions which obtain in the North Atlantic.

Countermining Requirements. When the explosion of one mine sets off another in the vicinity through actuation of its firing circuit, the second mine is said to have countermined. Usually it is most important that this shall not happen, for if mines are susceptible to countermining there is a risk of a whole minefield blowing up if one mine fires, or if the enemy explodes a charge in the vicinity.

With buoyant contact mines, it was generally possible to design mineshells and components so that they would withstand the shock of a mine explosion 100–150 feet away. Early non-contact magnetic buoyant and ground mines were found to be more susceptible to countermining, and anti-countermining switches were then introduced. These were generally designed to open the firing circuit before a firing potential due to shock could be developed in it.

Shock waves generated by underwater explosions travel considerable distances through the ground, and it was necessary to give countermine protection to magnetic ground mines at distances of several miles from an explosion, particularly if the latter also occurs on the sea-bed. Alternative magnetic circuits which require a reversal of magnetic field to actuate them, and which are countermine proof, have since been devised, and have other advantages.

With other firing systems, notably acoustic ones, it is possible to employ electrical filter networks to distinguish between the noise of an approaching ship and the explosion wave from the detonation of a charge. The latter has a very steep wave front, whereas the sound intensity due to a ship builds up much more slowly.

SAFETY REQUIREMENTS

Safety Requirements before Laying. The importance of ensuring safety before laying cannot be too highly stressed. The explosion of one mine on board a minelayer may result in the complete destruction of the ship and her crew.

All British mines have duplicate safety arrangements. Until the mine is either laid, or is a safe distance from the laying vessel, or aircraft, the electric detonator is kept at a safe distance away from the primer, preferably with a shutter interposed, and is also isolated electrically from the firing circuit. The physical separation of detonator and primer is achieved in ground mines by a hydrostatically operated detonator "placer" which usually also provides an additional break in the electrical circuit. The main electrical break is provided by a hydrostatic switch in ground mines, and by a mooring switch in buoyant mines. In the latter case, the switch is "made" only after the full mine-buoyancy force has come on the mooring rope. If the mine breaks adrift, the switch opens under the action of a strong internal spring, even should a considerable weight of mooring rope still be hanging from the mooring lever (Fig. 19). The arrangement of watertight joint and rocking lever illustrated has the advantage that, unlike types employing flat diaphragms, the performance is sensibly independent of the water pressure, and hence on the depth setting.

Very careful attention must be given to the mechanical design of safety devices. Their action must be simple and direct, with no possibility of breakage or jamming. There must be a visual indication on the outside of the mine as to whether it is "safe" or "active". It must be impossible for the mechanism to be "live" while the safety pins are inserted, and conversely, it must be impossible to insert the safety pins while the mechanism is live. These requirements often necessitate working to close

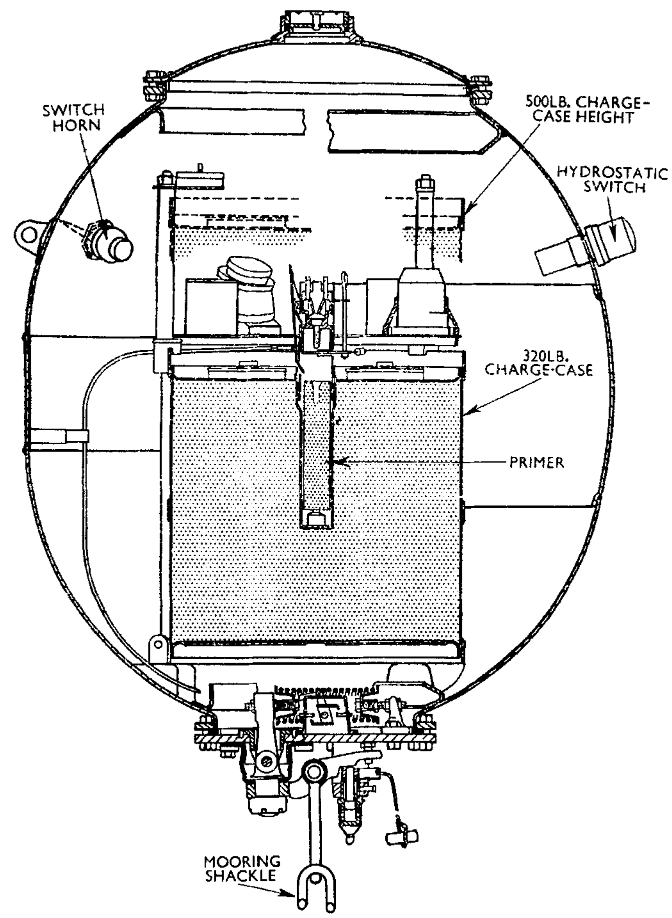


Fig. 19. Longitudinal Section of Buoyant Mine (British) Showing Alternative Constructions

dimensional limits and always demand careful inspection. All nuts must be prevented from slackening, the design and actuation of the electrical contacts must be beyond criticism, and the electrical circuit must be obviously "open" when the detonator is assembled.

Detonators are inserted in the mines at as short an interval before laying as possible.

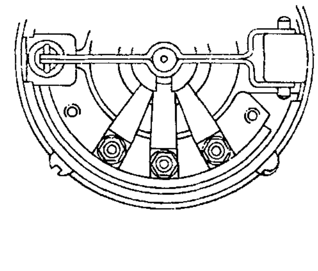
Arming and Sterilizing. To provide a further margin of safety to the laying craft it is usual to ensure that a mine cannot become live until some time after it has reached the sea-bed (ground mines), or has become moored (buoyant mines).

All detonator placing devices and primary control hydrostatic switches thus have two important safety features. Firstly, they have metal safety pins or fusing wires (p. 27) to prevent operation until such pins, etc., are withdrawn, which may be done by hand just before laying, or mechanically as the unit leaves the laying craft. Secondly, they have delay devices to retard operation after the safety pins have been withdrawn.

Plugs or rings of compressed chemicals form convenient delays for underwater weapons, and are usually incorporated in most hydrostatically operated arming devices to prevent operation until the chemical has dissolved. Materials must be selected which can be handled and exposed to the atmosphere for a considerable time without weakening or deliquescing. Delays ranging from a few minutes to a few hours are obtainable by this means. Control of the solution time may be effected by choice of material, by limiting the surface area of chemical exposed, and by controlling the removal of the solution products.

When longer arming delays are required, it is usual to employ clockwork—either mechanically or electrically driven. The starting of the clock may, however, be effected by a hydrostatic switch with a soluble plug delay.

For many purposes it is essential that mines shall become sterile after a certain time. This is usually achieved by employing a clockwork timing device either to disconnect the detonator from the firing circuit, or to short circuit the firing batteries (Fig. 20, Plate 2). Owing to the importance of the operation, it is usual to duplicate the equipment, or else to have special mechanisms which will produce the required result at the proper time, or earlier should they cease to run.



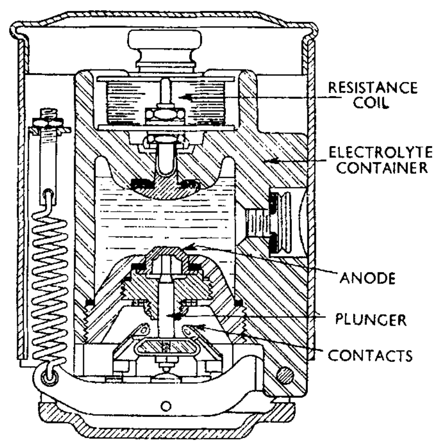


Fig. 21. Electrolytic Timing Device (British)

Owing to the difficulty of manufacturing clocks in this country during the war, alternative timing devices were developed. In the electrolytic timing switch (Fig. 21) the current from a dry battery passing through the cell removes the copper from the anode at a constant rate and when the anode is sufficiently weakened, it is penetrated by a spring-loaded plunger carrying electrical contacts. These contacts control circuits which sterilize the mine. The value of the current passing through the cell is determined by a resistance mounted on the cell. Different resistances are fitted to give operation in one, two, three, four, etc., weeks as required, with limits of accuracy of +0 to −30 per cent.

With buoyant mines, it is usual to arrange that the sterilizing device shall flood and sink the mine. This is conveniently done by allowing the timing device to complete a circuit through a battery and an explosive fuze. Firing of the latter propels a piston through a copper disk mounted in the mineshell, thus allowing the sea water to enter.

A simple self-contained electrolytic device has also been developed for the same purpose (Fig. 22). A thin steel disk, acting as an anode, and insulated from, though forming part of, the mineshell, is connected electrically through a resistance coil inside the mine with a cathode of silver and fuzed silver chloride exposed to the sea water, but otherwise electrically insulated from the anode and from the mineshell. When the unit is laid in the sea, the sea water acts as the electrolyte. The steel disk is corroded away at a predetermined rate, and ultimately punctures, admitting water to the interior of the mine. Different rates of corrosion of the anode are obtained by using coils of different resistance.

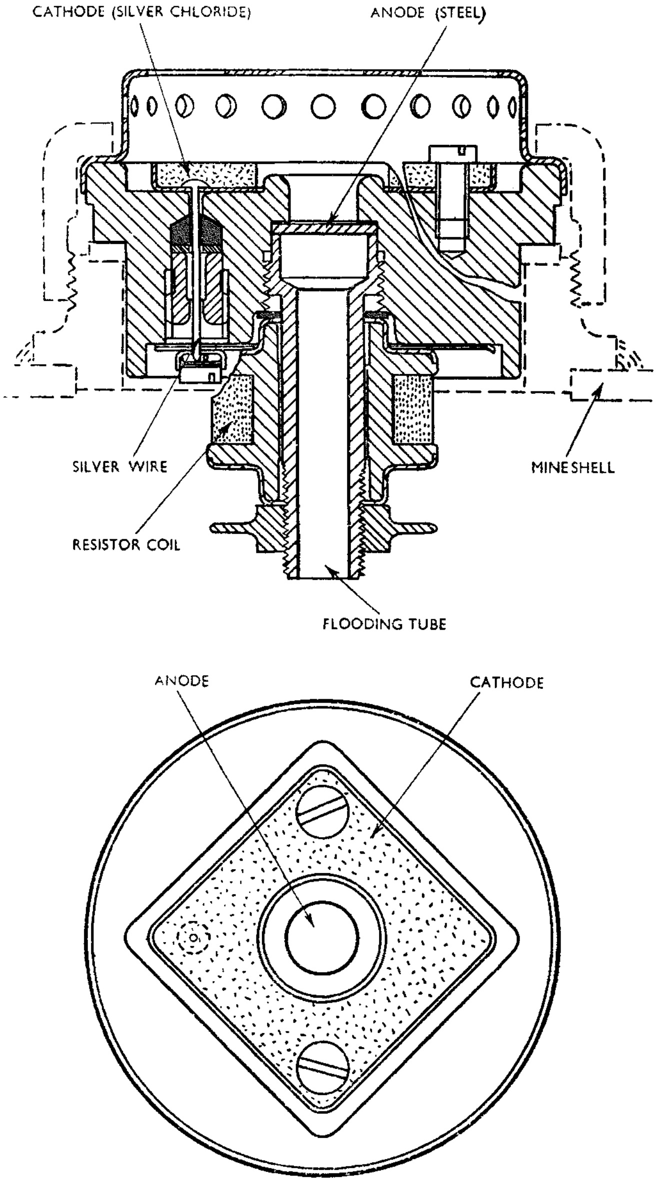


Fig. 22. Electrolytic Flooder (British)

FIRING PRINCIPLES

Principle of Operation of Some Firing Systems. It is possible to touch only very briefly on some of the methods of firing employed in naval mines.

Before the 1914–18 war, buoyant mines almost invariably operated on contact only. In the wars of 1914–18 and 1939–45, however, large numbers of buoyant antennae mines were also employed. In these, bronze or copper antennae, insulated from the steel mineshell and from the steel mooring rope, are fitted above and below the mine (Fig. 23). When one of these antennae is touched by a steel vessel, a sea cell is formed at the point of contact. A small proportion of the current in the system passes through that part of the circuit inside the mine, and this can be used to actuate a relay and fire the detonator. Different arrangements of antennae are used to meet the different requirements.

Successful buoyant magnetic mines were also developed prior to 1939. In the British system, a mumetal rod, carrying several thousand turns of copper wire, extends the length of the mine, the end plates acting as intensifiers. Any movement of the coil which causes it to cut lines of the earth's magnetic field, or any change in this field at the mine caused by movement of a large body of iron, such as a ship, will generate a current in the coil which may actuate the firing circuit.

Perturbation currents generated by movement of the mine, if large enough, will cause the mine to fire even in the absence of a target. Very occasionally, however, the effect may be useful, as when a fast motor torpedo boat, itself incapable of actuating the mine magnetically, may do so with its wash.

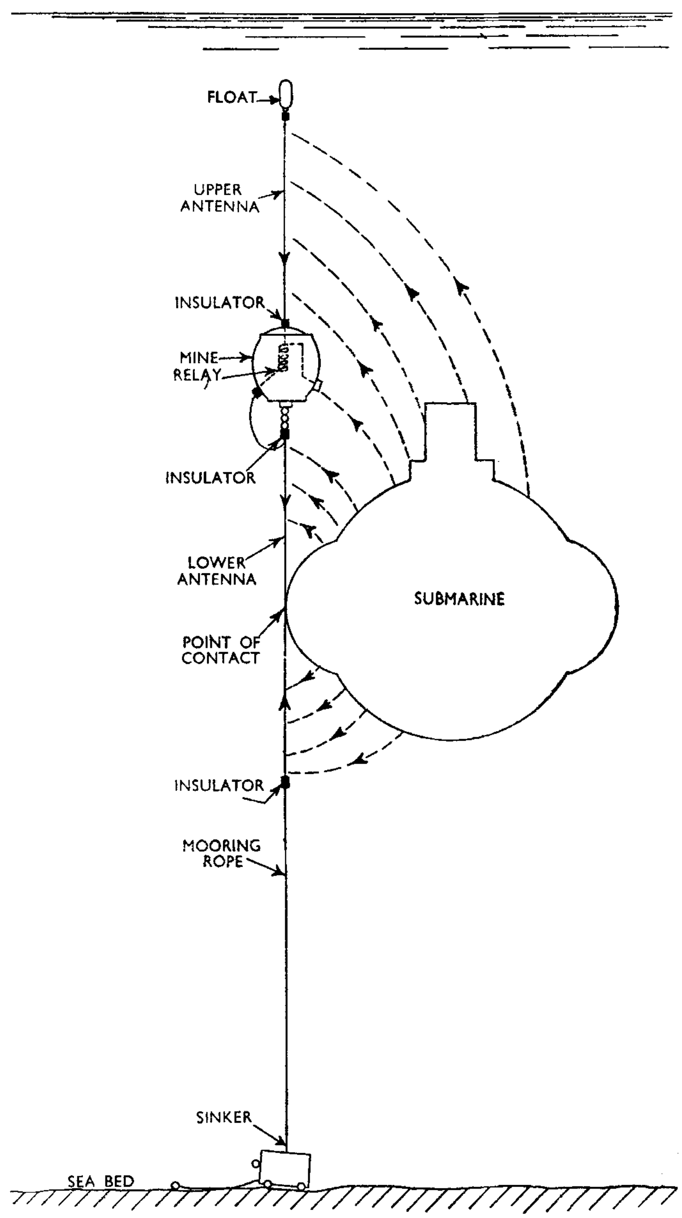


Fig. 23. Principle of Operation of Antenna Mine

Sea water return paths indicated by dotted lines.

The same magnetic system of firing has also been applied to ground mines. Greater sensitivities may here be employed, owing to the absence of perturbation currents.

In the first German magnetic firing system, a magnet, retained in a horizontal position by means of a torsion spring, was pivoted in a frame which was mounted in a complete and very freely moving gimbal system, to enable the magnet to orientate itself with the horizontal component of the earth's magnetic field (Fig. 24, Plate 2). A variation in the vertical component of the earth's magnetic field, such as may be caused by the passage of a ship, deflected the needle and actuated the firing circuit.

In latter designs, the size of the unit was reduced by employing vertical mumetal rods to concentrate the lines of force in a horizontal gap in which a disk of magnetic material, magnetized along a diameter, was pivoted under the control of a torsion spring. This unit also operates on changes in the vertical component of the earth's magnetic field. Unfortunately space does not permit of a full description of these interesting units being given.

The underwater acoustic characteristics of the ships have now been explored fairly thoroughly, and pick-up systems working on various frequencies from 20 cycles per second upwards have been devised and employed. The techniques developed for telephony and sound recording and reproduction are being generally exploited. The large drain on batteries which would occur if amplifiers were continually in operation is avoided by using some form of trigger system, i.e. a magnetic actuation may be utilized to switch on the amplifiers and make the acoustic system receptive to ship's noise. This technique also increases the difficulty of sweeping, since the minesweepers must employ more than one method of actuation, in special sequence, and perhaps with definite time intervals.

The hydrodynamic pressure effects of moving ships have also been used to actuate firing systems. With a ship in motion, there is a constant movement of water outwards and back from the bow, and inwards at the wake. Such flow is accompanied by a reduction in hydrostatic pressure beneath the ship. The pressure changes occurring at the sea-bed are complex, but sufficiently regular in character to be utilized. Pressure changes at the sea-bed also occur due to waves and swell, and the problem is to produce a mechanism capable of differentiating between the two series of effects.

In the German unit (Fig. 25, Plate 3) a very thin aluminium diaphragm is clamped at its periphery and allowed a maximum central deflexion of a few thousandths of an inch. The air in the system is confined by a rubber bag on the one side of the diaphragm. Slow pressure changes applied to the bag are equalized on each side of the diaphragm by means of a very small leak hole. More rapid changes deflect the diaphragm, completing an electrical circuit between a stirrup on the diaphragm and a fixed contact, and so actuating the mine.

DESIGN DETAILS

Details of Design of Mineshells and Fittings. The objective, with British mines, has for a long time been to design effective units which can be produced by the simplest manufacturing processes, using low-grade materials.

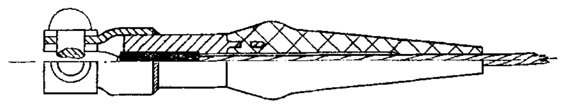
During the war, cold-pressing methods were widely exploited for hemispheres for buoyant mines and produced 60 per cent of the total output. Hemispheres 41 inches in diameter are pressed from $\frac{3}{16}$-inch thick plate without interstage annealing. The minimum permissible thickness is 0·170 inch at the greatest diameter, falling to 0·155 inch at the bottom of the hemisphere. Fully automatic methods of arc welding hemispheres together or to mine belts have also been developed. Such shells will withstand external pressures of 350 lb. per sq. in. before collapsing. Buoyant mines with removable charge cases require a large opening at one end. In British designs, the shell is spun or pressed over a machined bolt ring and a rubber ring between the unmachined surfaces of the plates makes the watertight joint between shell and cover (Fig. 19). The mouthpiece stiffening ring may be a symmetrical section rolled from strip.

Full use has been made in the application of presswork, welding, and up-to-date production methods to fittings and components. Complex jig welding fixtures are employed where necessary. Considerable use has been made of precision iron castings to enable machining to be reduced to a minimum.

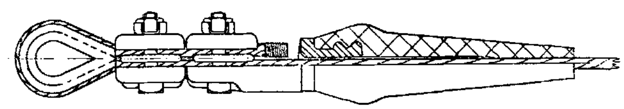
The modern method of swaging fittings or ferrules on to wire rope has proved itself to be far superior to older methods employing cast white metal cones, or clamp type grips (Fig. 26). No case of failure in service due to pulling out or fracture of the rope at the swage has been reported from the many thousands manufactured.

Although no difficulty is encountered in uniformly winding 100 or 200 fathoms of $1\frac{5}{16}$-inch or $1\frac{1}{4}$-inch circumference rope on to a 6-inch diameter barrel, it is found, when winding 1,000 fathoms of $\frac{3}{4}$-inch rope on to a 12-inch barrel, that the result is unsatisfactory unless the first layer is wound as in Fig. 27, otherwise the winding builds up in a very irregular manner. The easiest way to ensure this is to cast the appropriate ridges and grooves on the barrel.

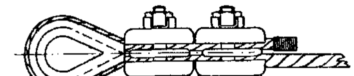
For ground mines, considerable attention has been given to the design of shells considered as part of magnetic and acoustic



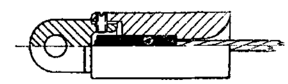
(*a*) Swage fitting with rubber protector.



(*b*) Rope grips with rubber protector.



(*c*) Rope grips only.

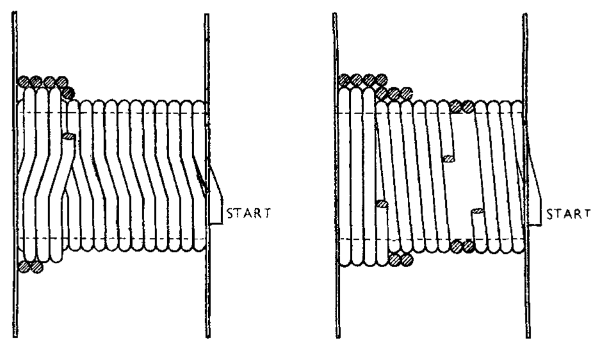


(*d*) Swage fitting only.

(*e*) White-metal cone with rubber protector.

Fig. 26. End Fittings for Mooring Ropes (British)

pick-up systems, and also from the point of view of strength. Although not designed to act as bombs, occasions have arisen where mines have been fitted with impact firing devices to cause them to detonate immediately should they strike solid ground. Under these conditions, the mineshell must not break up too easily.



Correct. Incorrect.

Fig. 27. Methods of Winding Mooring Rope Drums

The technique of welding thick aluminium alloy sections was developed by the Germans to a high degree of perfection, although the amount of machining employed by them was greater than in British designs.

British and German practice in sinker design was very similar. German mooring rope, however, size for size, was built up from much smaller diameter wire.

Details of Component Design. In British aircraft-laid ground mines, a special welded sheet metal container, with individual pockets, carries the components, each mounted separately in sponge rubber to provide insulation against shocks.

Components for buoyant mines may be assembled on the underside of the mine cover or on a platform fitted to the top of the charge case (Fig. 28, Plate 3).

An interesting method of mounting components was used in the German bomb mine (Fig. 4). Here the components were placed in pockets cut in a block of wood (Fig. 29, Plate 3), the interstices being filled with pitch.

It will be impossible, on account of space limitations, to do more than touch upon the mechanical features of a few typical components.

In the hydrostatic safety switch (Fig. 30) moulded insert silver contacts in the synthetic resin contact barrel make or break contact with the spring switch blades when the main spindle moves inwards under hydrostatic pressure. Operation may be delayed by employing a ring type soluble plug on the outer end

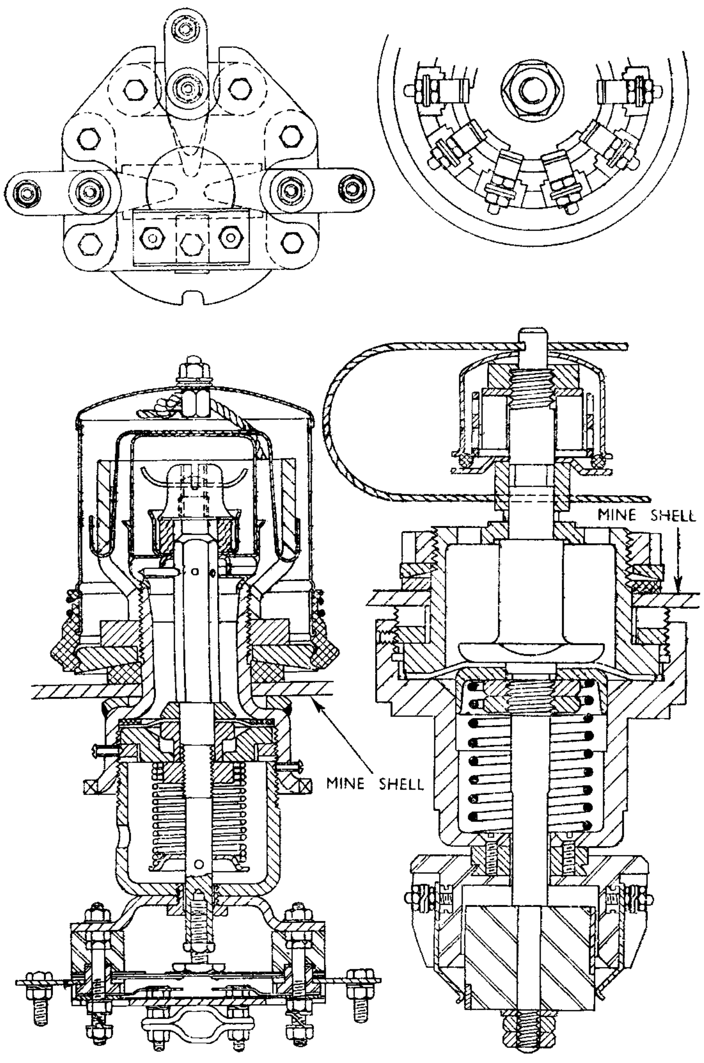


Fig. 30. Hydrostatic Switches (British)

of the spindle. Co-axial holes through the spindle and the switch body, respectively, carry the fuzing wire which provides a positive lock for the spindle in the safe position.

When a hydrostatic switch must return to the "off", or outer, position under spring control should a mine come to the surface, even after one or two years' immersion, an anti-fouling paste may be placed inside the switch to delay the formation of marine growth. All crevices likely to trap sand, or marine growth, which would prevent the return of the spindle and diaphragm, should be avoided.

Sensitive relays (Fig. 31, Plate 3) form an important item of modern influence mine-firing systems. Such relays operate reliably on currents as small as five micro-amperes. They have to be capable of withstanding severe laying shocks, and to show constancy of calibration in all positions. The contact pressures are of the order of 0·3 milligram per micro-ampere and great care has to be given to the selection of the contact materials and to the methods of mounting and cleaning them. The wire, suspension, coil former, and associated parts must be free from magnetic effects. The suspensions are specially rolled and the method of attachment to the spring tensioning devices must avoid weakening at these points.

Acoustic pick-ups are bolted directly to a portion of the mine-shell which is found to respond well to sound vibrations of the appropriate frequency and must, therefore, be robust. A typical unit (Fig. 32, Plate 3) consists of a spring steel cantilever, clamped to a rigid steel block, and having a small contact anvil at its outer end. Mounted on a tensioned cross-wire is a light balanced arm, carrying a contact which engages with the anvil on the main cantilever. Initial adjustment of the contact pressure is made by rotating the tensioning devices. Under static conditions the contacts have a steady electrical resistance of low value. When the pick-up is excited near the resonant frequency of the cantilever, the small movement causes the contact pressure to vary or the contacts to separate, causing variations in the contact resistance. As a constant e.m.f. is maintained across the contacts, excitation of the pick-up produces a fluctuating current which can be used in various ways to actuate the mine.

Where numerous small electrical components are employed, it is very convenient to mount them all in a box and fill the interstices with wax. Besides assisting in maintaining high electrical insulation, the wax provides a valuable support to the components both against shock loads, and against vibration, which may be quite severe during transport and carriage on the minelayer. Fig. 33, Plate 4, shows an amplifier, built on this system, before being waxed into the casing.

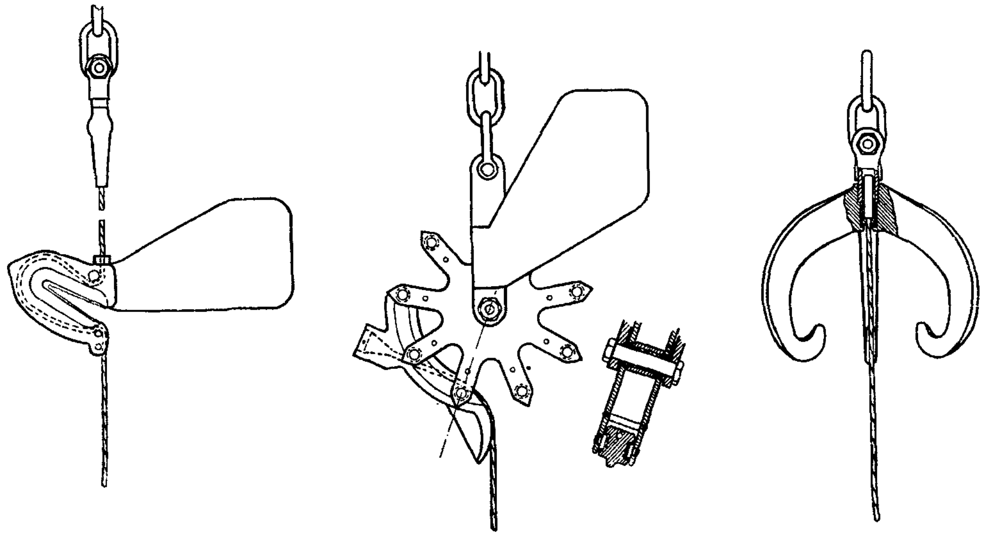
Component design is still far from finality. With most of the firing circuits devised and used during the war, speed of introduction into service was a major requirement, and components were often based on commercial or other existing instruments, or else the first successful design produced had to be put straight into production.

Anti-Sweeping Features and Devices. This survey would be incomplete without some reference to anti-sweeping devices.

Three devices for use with buoyant mines against wire sweeps are shown in Fig. 34. In the static cutter, Fig. 34*a*, two hardened nickel-chromium steel blades with sharp serrated teeth are mounted at a small angle to one another in a rigid steel frame. When a sweep rope engages the mine mooring rope and pulls it through the water, the rudder on the cutter frame swings this round to the correct orientation for the cutter blades to receive the sweep rope. The force required to cut the sweep rope is surprisingly small. The obstructor (Fig. 35, Plate 4), using static cutters, was specially designed for mixing with moored mines for the purpose of harassing sweepers. The sprocket wheel, or sweep evader (Fig. 34*b*), when incorporated in a mine mooring rope, makes it possible for a sweep rope to pass through the mooring without permanently severing it. With the grapnel (Fig. 34*c*), the sweep runs up the rope into the device and may cut the mooring rope, but the mine remains hooked to the sweep. If two or more mines are collected, an explosion is probable.

Ground mines are almost invariably swept by remote action, and a different evasion technique is, therefore, employed. Most complex firing circuits are evolved mainly to make sweeping difficult and generally require magnetic, acoustic or other impulses in certain sequences, strengths or time intervals. Obviously the possible variations are very great. Sequence switches may be driven electrically or by clockwork. They are triggered by one actuation circuit, and stop when a cycle is completed unless meanwhile the second type of actuating signal has been received and the mine exploded.

Mention should also be made of the ship counter. When incorporated, it may be set to delay firing until any desired actuation up to a certain number. By judicious assessment of the probabilities, based on a knowledge of the enemy's sweeping technique, it is sometimes possible to evade the sweepers, and to catch the convoy which follows. Two types of ship's counter are shown in Fig. 36, Plate 4. Delay devices are usually incorporated to ensure that the passage of a ship or sweep will not cause more than one actuation.



a Static cutter. *b* Sprocket or sweep evader. *c* Grapnel.

Fig. 34. Anti-Sweeping Devices for Buoyant Mines (British)

CONCLUSION

In the 1939–45 war, naval mining achieved considerable strategic importance. Approximately 206,000 buoyant mines, and 57,000 ground mines, were laid by British ships and aircraft, and no fewer than 1,588 enemy vessels were sunk or severely damaged by them.

The mines which have been described may be regarded as representative of the predominant types. Other types are used in smaller numbers for such duties as harbour defence, beach defence, and for special operations, but lack of space prevents any description being given.

Acknowledgements. As the schemes and devices described are the products of many minds, it is impossible to make individual acknowledgement, but having drawn freely on their work, the author would like to express his thanks to his colleagues, past and present, in the Admiralty Mining Establishment. His thanks are also due to the Admiralty for permission to publish the paper.

[For discussion and communications see pp. 44 and 50 respectively.]